Topics in Metallurgy for Gas Engineering

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Las Vegas, NV

Outline

- What is Element?
- What is Material Science & Engineering?
- What is a Steel?
- Metallurgy and Types of Stainless Steel
- High Temperature Behavior of Steels
- Failure Mechanisms
- Corrosion Behavior of Materials
- Failure Analysis

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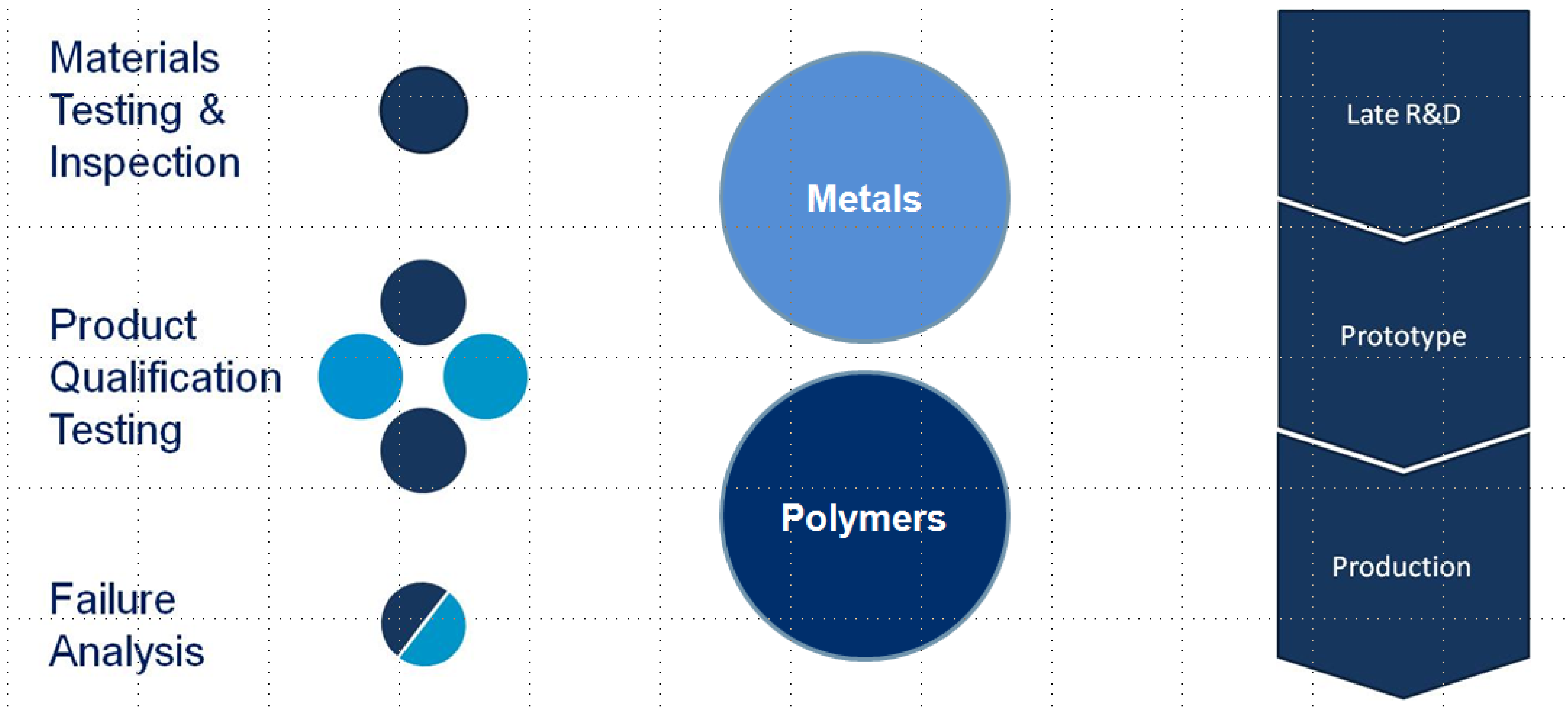

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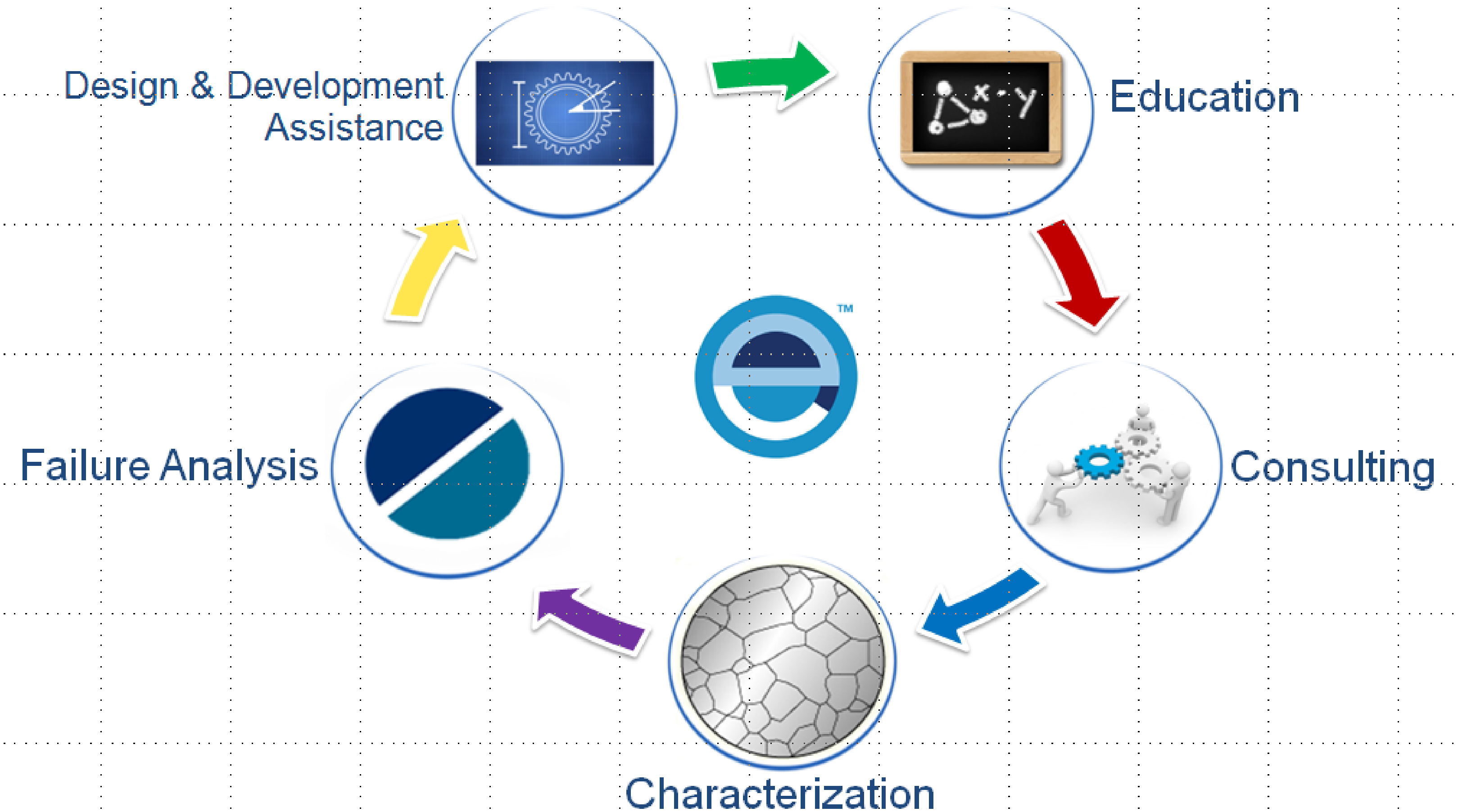

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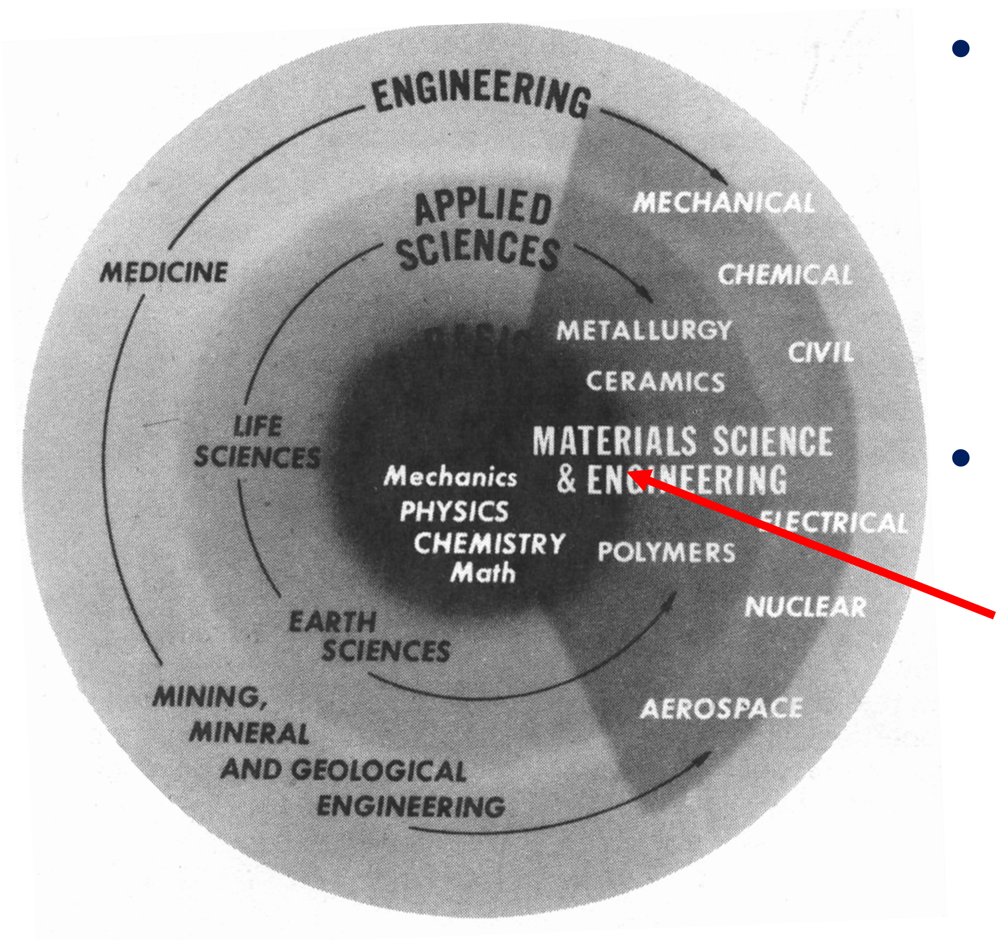
Role of the Materials Field



- Materials is the “glue function” between
  - fundamental science (including chemistry & physics), and
  - the engineering disciplines that usually deliver directly to society
- With chemistry and physics in the center of the “circle”,
  - the discipline of materials is in the half-radius position, and
  - the designing engineering disciplines are on the outer circumference

Reference: ASM Handbook

- Properties and Selection: Irons, Steels, and High Performance Alloys
- Tenth Edition
- ©1990
- ASM International
- Materials Park, OH

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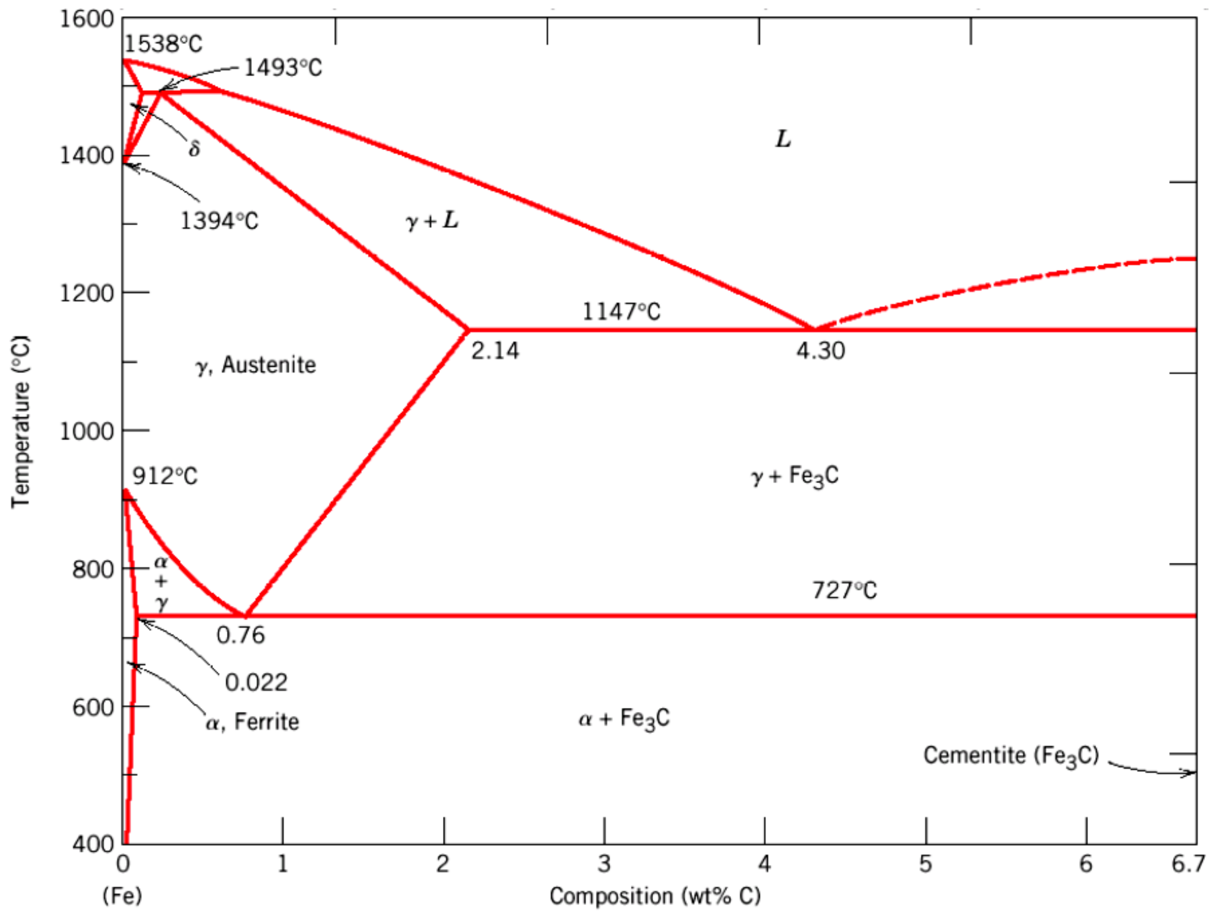
Iron- Iron/Carbide Diagram

- Standard Steels
  - Plain Carbon
  - Low Alloy Steels
- Austenite (ϒ) Transforms to:
  - Ferrite (α)
  - Cementite Fe_3C
  - Martensite
    - (when quenched)



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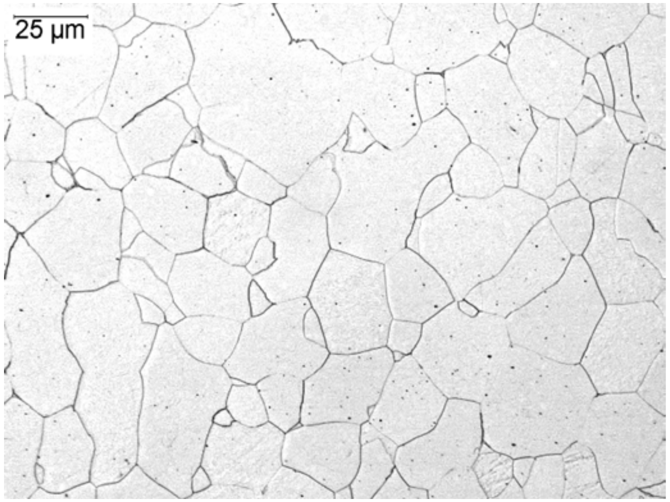
Standard Equilibrium Phases

- Slow cooling
- Ferrite

  &

- Cementite

  – Usually present in a mixture called Pearlite



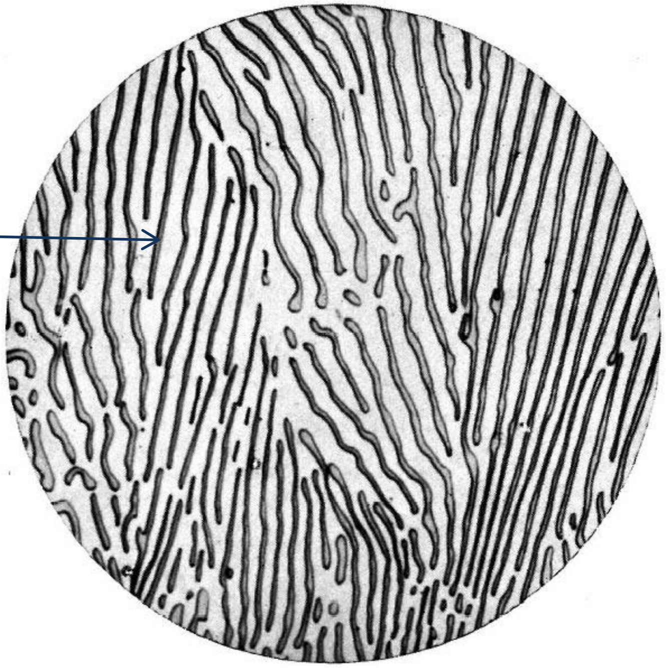


Fig. 22. Coarse pearlite formed at about 1325 F (720 C). Hardness: Rockwell C 5, 170 Bhn. 2500X. (Vilella)

Martensite

- Fast cooling

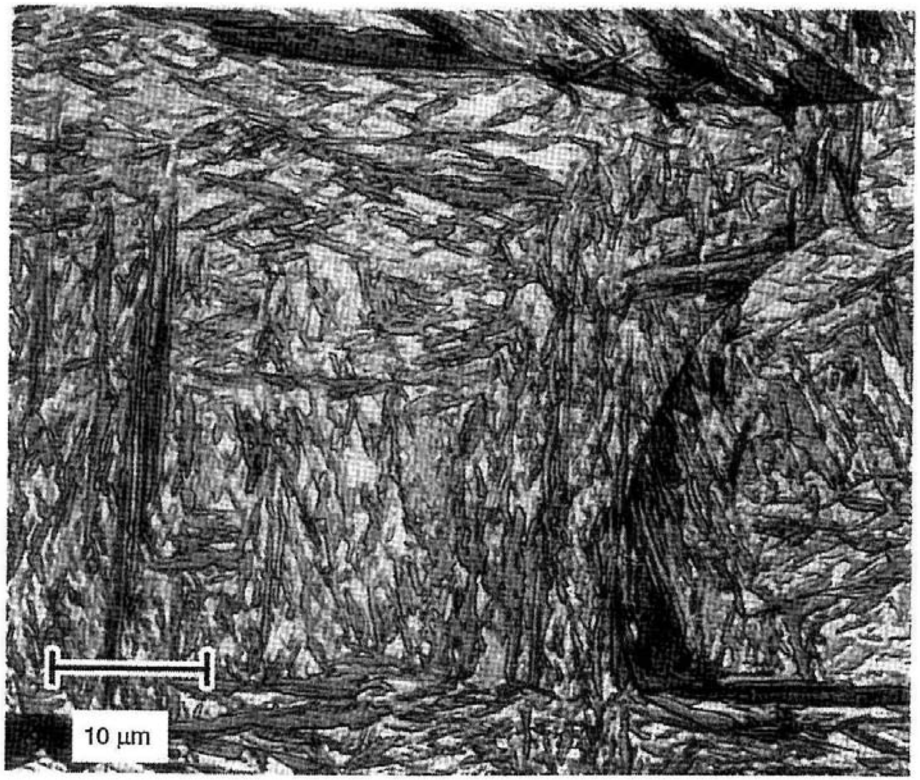


Fig. 42 Microstructure of quenched low-alloy steel showing plate martensite. 2% nital etch. Original magnification 1000×

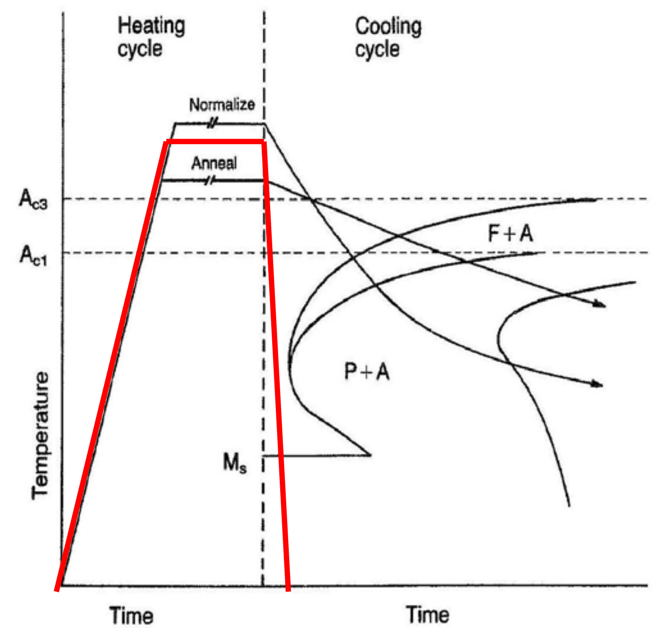


Fig. 5.4. Schematic time-temperature cycles for normalizing and full annealing. The slower cooling of annealing results in higher temperature transformation to ferrite and pearlite and coarser microstructures than does normalizing. Courtesy of M.D. Geib, Colorado School of Mines, Golden

Ferrite & Ferrite-Pearlite Steels

- Ferrite
- Ferrite-pearlite
  - More carbon
- Can also have some alloy
  - Usually Ni, Cr, Mo
  - Numbered 4xxx, 8xxx, etc.

Table 13 Carbon steel compositions
Applicable only to structural shapes, plates, strip, sheets, and welded tubing

UNS number	SAE-AISI number	Cast or heat chemical ranges and limits, %(a) C	Mn	P max	S max
G10060	1006	0.08 max	0.45 max	0.040	0.050
G10080	1008	0.10 max	0.50 max	0.040	0.050
G10090	1009	0.15 max	0.60 max	0.040	0.050
G10100	1010	0.08–0.13	0.30–0.60	0.040	0.050
G10120	1012	0.10–0.15	0.30–0.60	0.040	0.050
G10150	1015	0.12–0.18	0.30–0.60	0.040	0.050
G10160	1016	0.12–0.18	0.60–0.90	0.040	0.050
G10170	1017	0.14–0.20	0.30–0.60	0.040	0.050
G10180	1018	0.14–0.20	0.60–0.90	0.040	0.050
G10190	1019	0.14–0.20	0.70–1.00	0.040	0.050
G10200	1020	0.17–0.23	0.30–0.60	0.040	0.050
G10210	1021	0.17–0.23	0.60–0.90	0.040	0.050
G10220	1022	0.17–0.23	0.70–1.00	0.040	0.050
G10230	1023	0.19–0.25	0.30–0.60	0.040	0.050
G10250	1025	0.22–0.28	0.30–0.60	0.040	0.050
G10260	1026	0.22–0.28	0.60–0.90	0.040	0.050
G10300	1030	0.27–0.34	0.60–0.90	0.040	0.050
G10330	1033	0.29–0.36	0.70–1.00	0.040	0.050
G10350	1035	0.31–0.38	0.60–0.90	0.040	0.050
G10370	1037	0.31–0.38	0.70–1.00	0.040	0.050
G10380	1038	0.34–0.42	0.60–0.90	0.040	0.050
G10390	1039	0.36–0.44	0.70–1.00	0.040	0.050
G10400	1040	0.36–0.44	0.60–0.90	0.040	0.050
G10420	1042	0.39–0.47	0.60–0.90	0.040	0.050
G10430	1043	0.39–0.47	0.70–1.00	0.040	0.050
G10450	1045	0.42–0.50	0.60–0.90	0.040	0.050
G10460	1046	0.42–0.50	0.70–1.00	0.040	0.050
G10490	1049	0.45–0.53	0.60–0.90	0.040	0.050
G10500	1050	0.47–0.55	0.60–0.90	0.040	0.050

Aspects of Stainless Steels

- Phase diagrams
- Compositions
- Types and naming conventions
- Usage
- Microstructures

Stainless Steels (ss) – 3 types

- Ferritic
  - Chromium (Cr) and low carbon (C)
  - Annealed or strain hardened (worked)
  - Room or mildly elevated temperature usage
- Austenitic
  - Chromium (Cr), nickel (Ni) and low carbon (C)
  - Annealed or strain hardened
  - Room or high temperature usage
- Martensitic
  - Chromium and high carbon
  - Hardening by quench and tempering heat treatment
  - Room temperature and wear resistant

Iron-Chromium Phase Diagram

- Ferrite (alpha-α)
  - Standard equilibrium phase at room temperature
- Sigma (σ)
  - Undesirable embrittling phase at room temperature

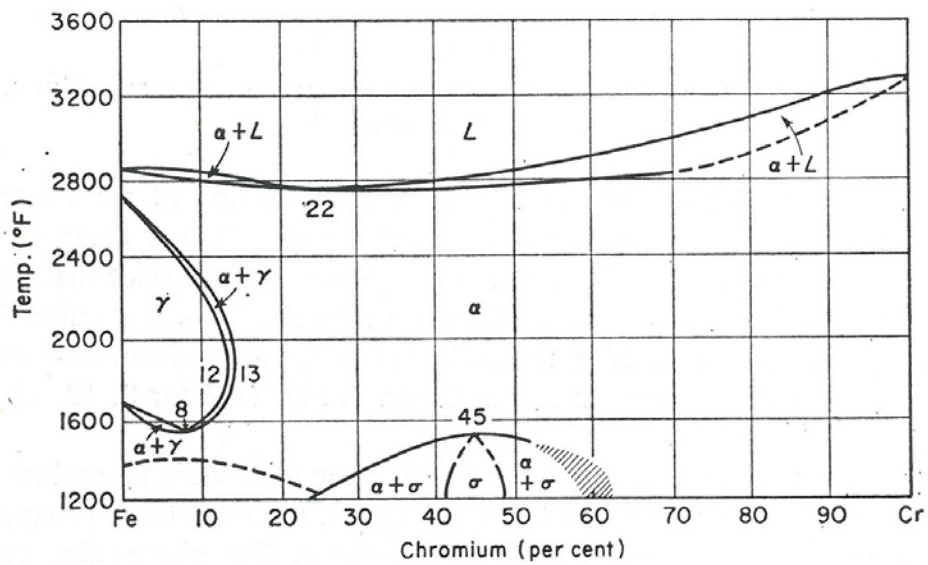


FIG. 14.1 Iron-chromium constitution diagram.

Effect of Ni on the Fe-Cr Diagram

a.k.a. How do you get an austenitic stainless steel?

- At least 13%Cr must be added to ferritic ss to avoid the "gamma (γ) loop" and get ferrite at all usage temperatures

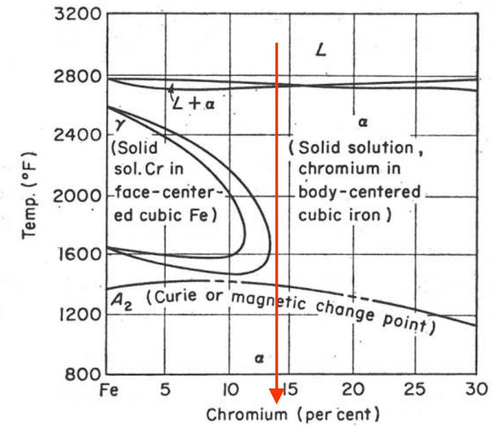


FIG. 14.2 Iron-rich end of iron-chromium constitution diagram. (Thum, *The Book of Stainless Steels*)

- With 8% Ni, austenite is stable at room temperature and all usage temperatures

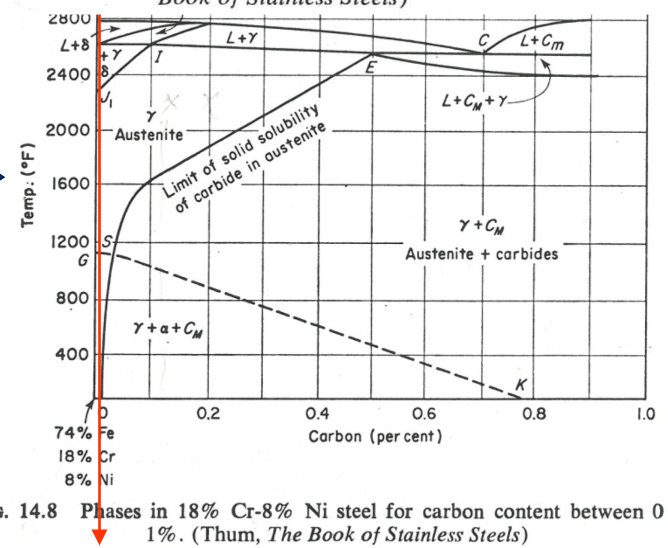


FIG. 14.8 Phases in 18% Cr-8% Ni steel for carbon content between 0 and 1%. (Thum, *The Book of Stainless Steels*)

Standard Ferritic Stainless Steels

- Three digits
- All begin with "4"
- Ti=titanium
- Se=selenium
- P=phosphorus
- S=sulfur

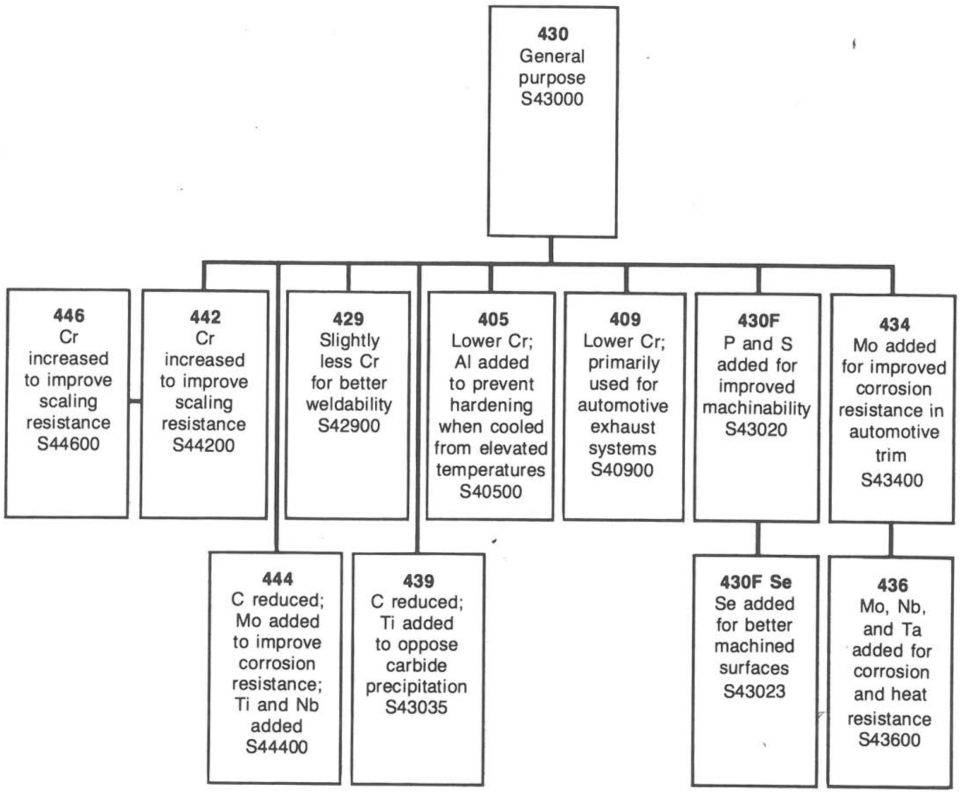


Fig. 2 Family relationships for standard ferritic stainless steels

Standard Martensitic Stainless Steels

- Three digits
- All begin with "4"
  - GGGroannnn!

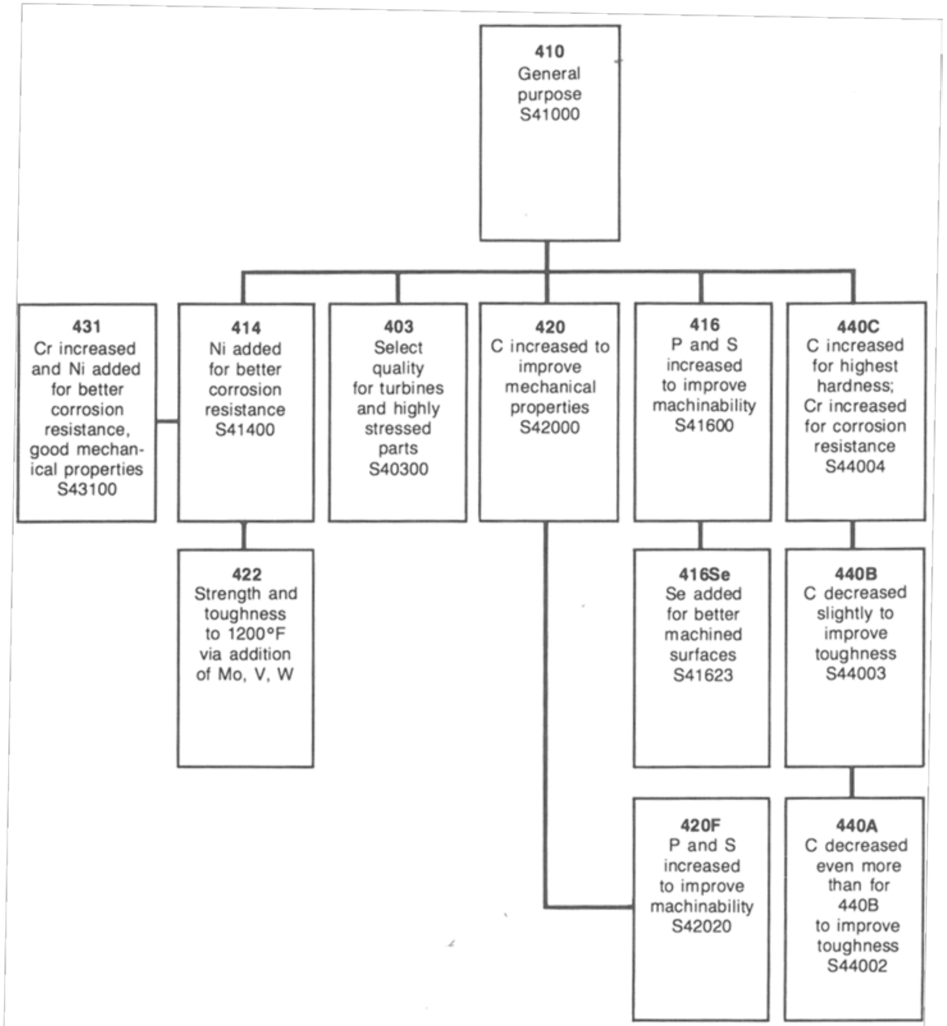


Fig. 3 Family relationships for standard martensitic stainless steels

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Standard Austenitic Steels

- Three digits
- Largest number
- All begin with “3”
  - YYYYYesss!
- Being replaced by Unified Numbering System (UNS) 5 digits
  - 304SS = S30400

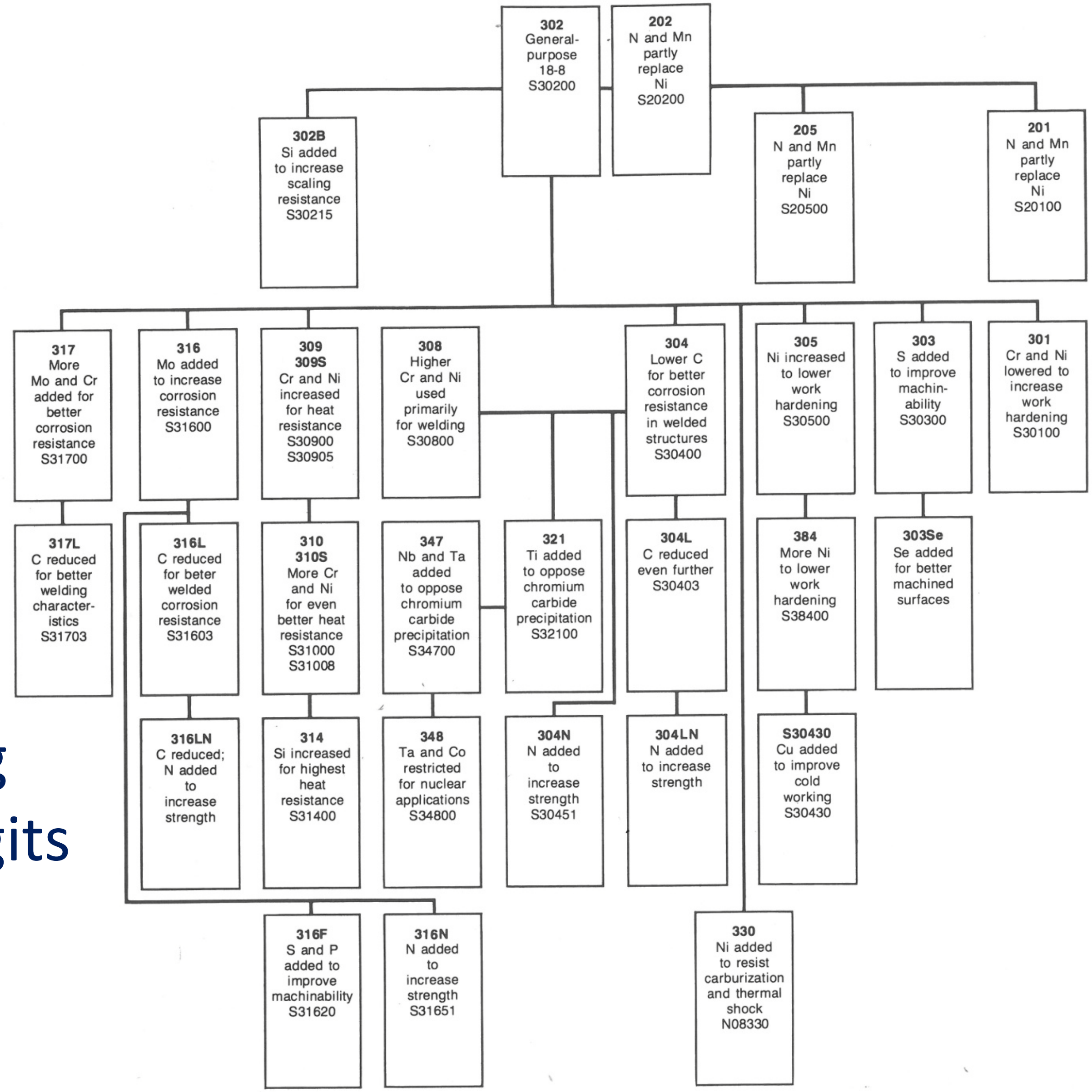


Fig. 1 Family relationships for standard austenitic stainless steels

Standard Austenitic Alloys

Type	UNS designation	Composition, %(a) C	Mn	Si	Cr	Ni	P	S	Other
Austenitic types									
201	S20100	0.15	5.5–7.5	1.00	16.0–18.0	3.5–5.5	0.06	0.03	0.25 N
202	S20200	0.15	7.5–10.0	1.00	17.0–19.0	4.0–6.0	0.06	0.03	0.25 N
205	S20500	0.12–0.25	14.0–15.5	1.00	16.5–18.0	1.0–1.75	0.06	0.03	0.32–0.40 N
301	S30100	0.15	2.00	1.00	16.0–18.0	6.0–8.0	0.045	0.03	...
302	S30200	0.15	2.00	1.00	17.0–19.0	8.0–10.0	0.045	0.03	...
302B	S30215	0.15	2.00	2.0–3.0	17.0–19.0	8.0–10.0	0.045	0.03	...
303	S30300	0.15	2.00	1.00	17.0–19.0	8.0–10.0	0.20	0.15 min	0.6 Mo(b)
303Se	S30323	0.15	2.00	1.00	17.0–19.0	8.0–10.0	0.20	0.06	0.15 min Se
304	S30400	0.08	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.03	...
304H	S30409	0.04–0.10	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.03	...
304L	S30403	0.03	2.00	1.00	18.0–20.0	8.0–12.0	0.045	0.03	...
304LN	S30453	0.03	2.00	1.00	18.0–20.0	8.0–12.0	0.045	0.03	0.10–0.16 N
302Cu	S30430	0.08	2.00	1.00	17.0–19.0	8.0–10.0	0.045	0.03	3.0–4.0 Cu
304N	S30451	0.08	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.03	0.10–0.16 N
305	S30500	0.12	2.00	1.00	17.0–19.0	10.5–13.0	0.045	0.03	...
308	S30800	0.08	2.00	1.00	19.0–21.0	10.0–12.0	0.045	0.03	...
309	S30900	0.20	2.00	1.00	22.0–24.0	12.0–15.0	0.045	0.03	...
309S	S30908	0.08	2.00	1.00	22.0–24.0	12.0–15.0	0.045	0.03	...
310	S31000	0.25	2.00	1.50	24.0–26.0	19.0–22.0	0.045	0.03	...
310S	S31008	0.08	2.00	1.50	24.0–26.0	19.0–22.0	0.045	0.03	...
314	S31400	0.25	2.00	1.5–3.0	23.0–26.0	19.0–22.0	0.045	0.03	...
316	S31600	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo
316F	S31620	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.20	0.10 min	1.75–2.5 Mo
316H	S31609	0.04–0.10	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo
316L	S31603	0.03	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo
316LN	S31653	0.03	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo; 0.10–0.16 N
316N	S31651	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo; 0.10–0.16 N
317	S31700	0.08	2.00	1.00	18.0–20.0	11.0–15.0	0.045	0.03	3.0–4.0 Mo
317L	S31703	0.03	2.00	1.00	18.0–20.0	11.0–15.0	0.045	0.03	3.0–4.0 Mo
321	S32100	0.08	2.00	1.00	17.0–19.0	9.0–12.0	0.045	0.03	5 × %C min Ti
321H	S32109	0.04–0.10	2.00	1.00	17.0–19.0	9.0–12.0	0.045	0.03	5 × %C min Ti
330	N08330	0.08	2.00	0.75–1.5	17.0–20.0	34.0–37.0	0.04	0.03	...
347	S34700	0.08	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	10 × %C min Nb
347H	S34709	0.04–0.10	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	8 × %C min – 1.0 max Nb
348	S34800	0.08	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	0.2 Co; 10 × %C min Nb; 0.10 Ta
348H	S34809	0.04–0.10	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	0.2 Co; 8 × %C min – 1.0 max Nb; 0.10 Ta
384	S38400	0.08	2.00	1.00	15.0–17.0	17.0–19.0	0.045	0.03	...

- Add suffix letter(s) to 3 digit parent
- Here's where the UNS 4th & 5th digit really help

Nonstandard Austenitic Alloys

Everybody's got their favorite version of an austenitic ss!

Designation(a)	UNS designation	C	Mn	Si	Cr	Ni	P	S	Other
		Composition, %(b)							
Austenitic stainless steels									
Gall-Tough	S20161	0.15	4.00–6.00	3.00–4.00	15.00–18.00	4.00–6.00	0.040	0.040	0.08–0.20 N
203 EZ (XM-1)	S20300	0.08	5.0–6.5	1.00	16.0–18.0	5.0–6.5	0.040	0.18–0.35	0.5 Mo; 1.75–2.25 Cu
Nitronic 50 (XM-19)	S20910	0.06	4.0–6.0	1.00	20.5–23.5	11.5–13.5	0.040	0.030	1.5–3.0 Mo; 0.2–0.4 N; 0.1–0.3 Nb; 0.1–0.3 V
Tenelon (XM-31)	S21400	0.12	14.5–16.0	0.3–1.0	17.0–18.5	0.75	0.045	0.030	0.35 N
Cryogenic Tenelon (XM-14)	S21460	0.12	14.0–16.0	1.00	17.0–19.0	5.0–6.0	0.060	0.030	0.35–0.50 N
Esshete 1250	S21500	0.15	5.5–7.0	1.20	14.0–16.0	9.0–11.0	0.040	0.030	0.003–0.009 B; 0.75–1.25 Nb; 0.15–0.40 V
Type 216 (XM-17)	S21600	0.08	7.5–9.0	1.00	17.5–22.0	5.0–7.0	0.045	0.030	2.0–3.0 Mo; 0.25–0.50 N
Type 216 L (XM-18)	S21603	0.03	7.5–9.0	1.00	17.5–22.0	7.5–9.0	0.045	0.030	2.0–3.0 Mo; 0.25–0.50 N
Nitronic 60	S21800	0.10	7.0–9.0	3.5–4.5	16.0–18.0	8.0–9.0	0.040	0.030	0.08–0.18 N
Nitronic 40 (XM-10)	S21900	0.08	8.0–10.0	1.00	19.0–21.5	5.5–7.5	0.060	0.030	0.15–0.40 N
21-6-9 LC	S21904	0.04	8.00–10.00	1.00	19.00–21.50	5.50–7.50	0.060	0.030	0.15–0.40 N
Nitronic 33 (18-3-Mn)	S24000	0.08	11.50–14.50	1.00	17.00–19.00	2.50–3.75	0.060	0.030	0.20–0.40 N
Nitronic 32 (18-2-Mn)	S24100	0.15	11.00–14.00	1.00	16.50–19.50	0.50–2.50	0.060	0.030	0.20–0.45 N
18-18 Plus	S28200	0.15	17.0–19.0	1.00	17.5–19.5	...	0.045	0.030	0.5–1.5 Mo; 0.5–1.5 Cu; 0.4–0.6 N
303 Plus X (XM-5)	S30310	0.15	2.5–4.5	1.00	17.0–19.0	7.0–10.0	0.020	0.25 min	0.6 Mo
MVMA(c)	S30415	0.05	0.60	1.30	18.5	9.50	...	...	0.15 N; 0.04 Ce
304BI(d)	S30424	0.08	2.00	0.75	18.00–20.00	12.00–15.00	0.045	0.030	0.10 N; 1.00–1.25 B
304 HN (XM-21)	S30452	0.04–0.10	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.030	0.16–0.30 N
Cronifer 1815 LCSi	S30600	0.018	2.00	3.7–4.3	17.0–18.5	14.0–15.5	0.020	0.020	0.2 Mo
RA 85 H(c)	S30615	0.20	0.80	3.50	18.5	14.50	...	...	1.0 Al
253 MA	S30815	0.05–0.10	0.80	1.4–2.0	20.0–22.0	10.0–12.0	0.040	0.030	0.14–0.20 N; 0.03–0.08 Ce; 1.0 Al
Type 309 S Cb	S30940	0.08	2.00	1.00	22.0–24.0	12.0–15.0	0.045	0.030	10 × %C min to 1.10 max Nb
Type 310 Cb	S31040	0.08	2.00	1.50	24.0–26.0	19.0–22.0	0.045	0.030	10 × %C min to 1.10 max Nb + Ta
254 SMO	S31254	0.020	1.00	0.80	19.50–20.50	17.50–18.50	0.030	0.010	6.00–6.50 Mo; 0.50–1.00 Cu; 0.180–0.220 N
Type 316 Ti	S31635	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.030	5 × %(C + N) min to 0.70 max Ti; 2.0–3.0 Mo; 0.10 N
Type 316 Cb	S31640	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.030	10 × %C min to 1.10 max Nb + Ta; 2.0–3.0 Mo; 0.10 N
Type 316 HQ	...	0.030	2.00	1.00	16.00–18.25	10.00–14.00	0.030	0.015	3.00–4.00 Cu; 2.00–3.00 Mo
Type 317 LM	S31725	0.03	2.00	1.00	18.0–20.0	13.5–17.5	0.045	0.030	4.0–5.0 Mo; 0.10 N
17-14-4 LN	S31726	0.03	2.00	0.75	17.0–20.0	13.5–17.5	0.045	0.030	4.0–5.0 Mo; 0.10–0.20 N
Type 317 LN	S31753	0.03	2.00	1.00	18.0–20.0	11.0–15.0	0.030	0.030	0.10–0.22 N
Type 370	S37000	0.03–0.05	1.65–2.35	0.5–1.0	12.5–14.5	14.5–16.5	0.040	0.010	1.5–2.5 Mo; 0.1–0.4 Ti; 0.005 N; 0.05 Co
18-18-2 (XM-15)	S38100	0.08	2.00	1.5–2.5	17.0–19.0	17.5–18.5	0.030	0.030	...
19-9 DL	S63198	0.28–0.35	0.75–1.50	0.03–0.8	18.0–21.0	8.0–11.0	0.040	0.030	1.0–1.75 Mo; 0.1–0.35 Ti; 1.0–1.75 W; 0.25–0.60 Nb
20Cb-3	N08020	0.07	2.00	1.00	19.0–21.0	32.0–38.0	0.045	0.035	2.0–3.0 Mo; 3.0–4.0 Cu; 8 × %C min to 1.00 max Nb
20Mo-4	N08024	0.03	1.00	0.50	22.5–25.0	35.0–40.0	0.035	0.035	3.50–5.00 Mo; 0.50–1.50 Cu; 0.15–0.35 Nb
20Mo-6	N08026	0.03	1.00	0.50	22.00–26.00	33.00–37.20	0.03	0.03	5.00–6.70 Mo; 2.00–4.00 Cu
Sanicro 28	N08028	0.02	2.00	1.00	26.0–28.0	29.5–32.5	0.020	0.015	3.0–4.0 Mo; 0.6–1.4 Cu
AL-6X	N08366	0.035	2.00	1.00	20.0–22.0	23.5–25.5	0.030	0.030	6.0–7.0 Mo
AL-6XN	N08367	0.030	2.00	1.00	20.0–22.0	23.50–25.50	0.040	0.030	6.00–7.00 Mo; 0.18–0.25 N
JS-700	N08700	0.04	2.00	1.00	19.0–23.0	24.0–26.0	0.040	0.030	4.3–5.0 Mo; 8 × %C min to 0.5 max Nb; 0.5 Cu; 0.005 Pb; 0.035 S
Type 332	N08800	0.01	1.50	1.00	19.0–23.0	30.0–35.0	0.045	0.015	0.15–0.60 Ti; 0.15–0.60 Al
904L	N08904	0.02	2.00	1.00	19.0–23.0	23.0–28.0	0.045	0.035	4.0–5.0 Mo; 1.0–2.0 Cu
Cronifer 1925 hMo	N08925	0.02	1.00	0.50	24.0–26.0	19.0–21.0	0.045	0.030	6.0–7.0 Mo; 0.8–1.5 Cu; 0.10–0.20 N
Cronifer 2328	...	0.04	0.75	0.75	22.0–24.0	26.0–28.0	0.030	0.015	2.5–3.5 Cu; 0.4–0.7 Ti; 2.5–3.0 Mo

Standard Ferritic, Martensitic & Others

		Composition, %(a)							
Type	UNS designation	C	Mn	Si	Cr	Ni	P	S	Other
405	S40500	0.08	1.00	1.00	11.5–14.5	. . .	0.04	0.03	0.10–0.30 Al
409	S40900	0.08	1.00	1.00	10.5–11.75	0.50	0.045	0.045	6 × %C min − 0.75 max Ti
429	S42900	0.12	1.00	1.00	14.0–16.0	. . .	0.04	0.03	. . .
430	S43000	0.12	1.00	1.00	16.0–18.0	. . .	0.04	0.03	. . .
430F	S43020	0.12	1.25	1.00	16.0–18.0	. . .	0.06	0.15 min	0.6 Mo(b)
430FSe	S43023	0.12	1.25	1.00	16.0–18.0	. . .	0.06	0.06	0.15 min Se
434	S43400	0.12	1.00	1.00	16.0–18.0	. . .	0.04	0.03	0.75–1.25 Mo
436	S43600	0.12	1.00	1.00	16.0–18.0	. . .	0.04	0.03	0.75–1.25 Mo; 5 × %C min − 0.70 max Nb
439	S43035	0.07	1.00	1.00	17.0–19.0	0.50	0.04	0.03	0.15 Al; 12 × %C min − 1.10 Ti
442	S44200	0.20	1.00	1.00	18.0–23.0	. . .	0.04	0.03	. . .
444	S44400	0.025	1.00	1.00	17.5–19.5	1.00	0.04	0.03	1.75–2.50 Mo; 0.025 N; 0.2 + 4 (%C + %N) min − 0.8 max (Ti + Nb)
446	S44600	0.20	1.50	1.00	23.0–27.0	. . .	0.04	0.03	0.25 N
Duplex (ferritic-austenitic) type									
329	S32900	0.20	1.00	0.75	23.0–28.0	2.50–5.00	0.040	0.030	1.00–2.00 Mo
Martensitic types									
403	S40300	0.15	1.00	0.50	11.5–13.0	. . .	0.04	0.03	. . .
410	S41000	0.15	1.00	1.00	11.5–13.5	. . .	0.04	0.03	. . .
414	S41400	0.15	1.00	1.00	11.5–13.5	1.25–2.50	0.04	0.03	. . .
416	S41600	0.15	1.25	1.00	12.0–14.0	. . .	0.06	0.15 min	0.6 Mo(b)
416Se	S41623	0.15	1.25	1.00	12.0–14.0	. . .	0.06	0.06	0.15 min Se
420	S42000	0.15 min	1.00	1.00	12.0–14.0	. . .	0.04	0.03	. . .
420F	S42020	0.15 min	1.25	1.00	12.0–14.0	. . .	0.06	0.15 min	0.6 Mo(b)
422	S42200	0.20–0.25	1.00	0.75	11.5–13.5	0.5–1.0	0.04	0.03	0.75–1.25 Mo; 0.75–1.25 W; 0.15–0.3 V
431	S43100	0.20	1.00	1.00	15.0–17.0	1.25–2.50	0.04	0.03	. . .
440A	S44002	0.60–0.75	1.00	1.00	16.0–18.0	. . .	0.04	0.03	0.75 Mo
440B	S44003	0.75–0.95	1.00	1.00	16.0–18.0	. . .	0.04	0.03	0.75 Mo
440C	S44004	0.95–1.20	1.00	1.00	16.0–18.0	. . .	0.04	0.03	0.75 Mo
Precipitation-hardening types									
PH 13-8 Mo	S13800	0.05	0.20	0.10	12.25–13.25	7.5–8.5	0.01	0.008	2.0–2.5 Mo; 0.90–1.35 Al; 0.01 N
15-5 PH	S15500	0.07	1.00	1.00	14.0–15.5	3.5–5.5	0.04	0.03	2.5–4.5 Cu; 0.15–0.45 Nb
17-4 PH	S17400	0.07	1.00	1.00	15.5–17.5	3.0–5.0	0.04	0.03	3.0–5.0 Cu; 0.15–0.45 Nb
17-7 PH	S17700	0.09	1.00	1.00	16.0–18.0	6.5–7.75	0.04	0.04	0.75–1.5 Al

(a) Single values are maximum values unless otherwise indicated. (b) Optional

- Difficult to discriminate ferritic versus martensitic, just by the 4xx number
- PH = Precipitation-Hardenable
  - Can't see the Mo, Al, N, Cu, Nb, intermetallic precipitates in the optical microscope
  - Can have austenitic, semiaustenitic, or martensitic PH ss

Nonstandard Others

Designation(a)	UNS designation	C	Mn	Si	Cr	Ni	P	S	Other
		Composition, %(b)							
Ferritic stainless steels									
18-2 FM (XM-34)	S18200	0.08	1.25–2.50	1.00	17.5–19.5	. . .	0.040	0.15 min	1.5–2.5 Mo
Type 430 Ti	S43036	0.10	1.00	1.00	16.0–19.5	0.75	0.040	0.030	5 × %C min to 0.75 max Ti
Type 441	S44100	0.03	1.00	1.00	17.5–19.5	1.00	0.040	0.040	0.3 + 9 × (%C) min to 0.90 max Nb; 0.1–0.5 Ti; 0.03 N
E-Brite 26-1	S44627	0.01	0.40	0.40	25.0–27.0	0.50	0.020	0.020	0.75–1.5 Mo; 0.05–0.2 Nb; 0.015 N; 0.2 Cu
MONIT (25-4-4)	S44635	0.025	1.00	0.75	24.5–26.0	3.5–4.5	0.040	0.030	3.5–4.5 Mo; 0.2 + 4 (%C + %N) min to 0.8 max (Ti + Nb); 0.035 N
Sea-Cure (SC-1)	S44660	0.025	1.00	1.00	25.0–27.0	1.5–3.5	0.040	0.030	2.5–3.5 Mo; 0.2 + 4 (%C + %N) min to 0.8 max (Ti + Nb); 0.035 N
AL 29-4C	S44735	0.030	1.00	1.00	28.0–30.0	1.00	0.040	0.030	3.60–4.20 Mo; 0.20–1.00 Ti + Nb and 6 (%C + %N) min Ti + Nb; 0.045 N
AL 29-4-2	S44800	0.01	0.30	0.20	28.0–30.0	2.0–2.5	0.025	0.020	3.5–4.2 Mo; 0.15 Cu; 0.02 N; 0.025 max (%C + %N)
18 SR(c)	. . .	0.04	0.30	1.00	18.0	. . .	. . .	. . .	2.0 Al; 0.4 Ti
12 SR(c)	. . .	0.02	. . .	0.50	12.0	. . .	. . .	. . .	1.2 Al; 0.3 Ti
406	. . .	0.06	1.00	0.50	12.0–14.0	0.50	0.040	0.030	2.75–4.25 Al; 0.6 Ti
408 Cb	. . .	0.03	0.2–0.5	0.2–0.5	11.75–12.25	0.45	0.030	0.020	0.75–1.25 Al; 0.65–0.75 Nb; 0.3–0.5 Ti; 0.03 N
ALFA IV	. . .	0.03	0.50	0.60	19.0–21.0	0.45	0.035	0.005	4.75–5.25 Al; 0.005–0.035 Ce; 0.03 N
Sealmet 1	. . .	0.08	0.5–0.8	0.3–0.6	28.0–29.0	0.40	0.030	0.015	0.04 N
Duplex stainless steels									
44LN	S31200	0.030	2.00	1.00	24.0–26.0	5.50–6.50	0.045	0.030	1.20–2.00 Mo; 0.14–0.20 N
DP-3	S31260	0.030	1.00	0.75	24.0–26.0	5.50–7.50	0.030	0.030	2.50–3.50 Mo; 0.20–0.80 Cu; 0.10–0.30 N; 0.10–0.50 W
3RE60	S31500	0.030	1.20–2.00	1.40–2.00	18.00–19.00	4.25–5.25	0.030	0.030	2.50–3.00 Mo
2205	S31803	0.030	2.00	1.00	21.0–23.0	4.50–6.50	0.030	0.020	2.50–3.50 Mo; 0.08–0.20 N
2304	S32304	0.030	2.50	1.0	21.5–24.5	3.0–5.5	0.040	0.040	0.05–0.60 Mo; 0.05–0.60 Cu; 0.05–0.20 N
Uranus 50	S32404	0.04	2.00	1.0	20.5–22.5	5.5–8.5	0.030	0.010	2.0–3.0 Mo; 1.0–2.0 Cu; 0.20 N
Ferralium 255	S32550	0.04	1.50	1.00	24.0–27.0	4.50–6.50	0.04	0.03	2.00–4.00 Mo; 1.50–2.50 Cu; 0.10–0.25 N
7-Mo PLUS	S32950	0.03	2.00	0.60	26.0–29.0	3.50–5.20	0.035	0.010	1.00–2.50 Mo; 0.15–0.35 N
Martensitic stainless steels									
Type 410S	S41008	0.08	1.00	1.00	11.5–13.5	0.60	0.040	0.030	. . .
Type 410 Cb (XM-30)	S41040	0.15	1.00	1.00	11.5–13.5	. . .	0.040	0.030	0.05–0.20 Nb
E4	S41050	0.04	1.00	1.00	10.5–12.5	0.60–1.1	0.045	0.030	0.10 N
CA6NM	S41500	0.05	0.5–1.0	0.60	11.5–14.0	3.5–5.5	0.030	0.030	0.5–1.0 Mo
416 Plus X (XM-6)	S41610	0.15	1.5–2.5	1.00	12.0–14.0	. . .	0.060	0.15 min	0.6 Mo
Type 418 (Greek Ascolloy)	S41800	0.15–0.20	0.50	0.50	12.0–14.0	1.8–2.2	0.040	0.030	2.5–3.5 W
TrimRite	S42010	0.15–0.30	1.00	1.00	13.5–15.0	0.25–1.00	0.040	0.030	0.40–1.00 Mo
Type 420 F Se	S42023	0.3–0.4	1.25	1.00	12.0–14.0	. . .	0.060	0.060	0.15 min Se; 0.6 Zr; 0.6 Cu
Lapelloy	S42300	0.27–0.32	0.95–1.35	0.50	11.0–12.0	0.50	0.025	0.025	2.5–3.0 Mo; 0.2–0.3 V
Type 440 F	S44020	0.95–1.20	1.25	1.00	16.0–18.0	0.75	0.040	0.10–0.35	0.08 N
Type 440 F Se	S44023	0.95–1.20	1.25	1.00	16.0–18.0	0.75	0.040	0.030	0.15 min Se; 0.60 Mo
Precipitation-hardening stainless steels									
PH 14-4 Mo	S14800	0.05	1.00	1.00	13.75–15.0	7.75–8.75	0.015	0.010	2.0–3.0 Mo; 0.75–1.50 Al
PH 15–7 Mo (Type 632)	S15700	0.09	1.00	1.00	14.0–16.0	6.5–7.75	0.040	0.030	2.0–3.0 Mo; 0.75–1.5 Al
AM-350 (Type 633)	S35000	0.07–0.11	0.5–1.25	0.50	16.0–17.0	4.0–5.0	0.040	0.030	2.5–3.25 Mo; 0.07–0.13 N
AM-355 (Type 634)	S35500	0.10–0.15	0.5–1.25	0.50	15.0–16.0	4.0–5.0	0.040	0.030	2.5–3.25 Mo; 0.07–0.13 N
Custom 450 (XM-25)	S45000	0.05	1.00	1.00	14.0–16.0	5.0–7.0	0.030	0.030	1.25–1.75 Cu; 0.5–1.0 Mo; 8 × %C min Nb
Custom 455 (XM-16)	S45500	0.05	0.50	0.50	11.0–12.5	7.5–9.5	0.040	0.030	1.5–2.5 Cu; 0.8–1.4 Ti; 0.1–0.5 Nb; 0.5 Mo

Typical Austenitic SS Microstructures

- Annealing Twins
  - Straight parallograms within grains
  - Mirror images of adjacent structure
- Can only strain harden (deformation process)
  - Increases strength
  - Lowers ductility
  - Very heavy work leads to “deformation martensite” formation

Fig. 6 Type 304 stainless steel strip, annealed 5 min at 1065 °C (1950 °F), cooled in air. Structure consists of equiaxed austenite grains and annealing twins. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 250×

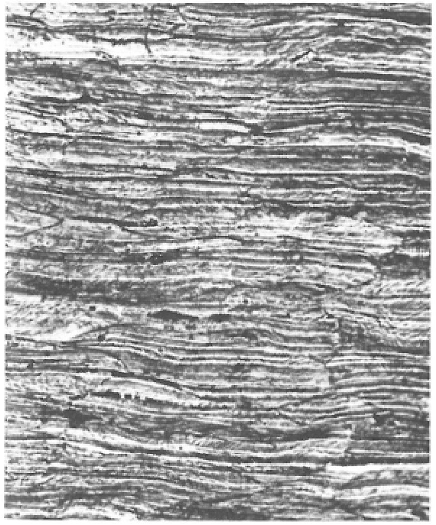


Fig. 4 Type 301 sheet, cold rolled to 40% reduction (full hard), showing almost complete transformation to martensite in severely deformed austenite grains. Electrolytic: 10% oxalic acid. 250×

Typical Ferritic Stainless Steel Microstructures

- Ferrite looks like austenite, except for its twins
- Chromium carbide forms at very low carbon contents, which is OK
  - Unless carbide films form adjacent to grain boundaries
  - Which causes "sensitization" denudes grain interiors of corrosion-protective Cr

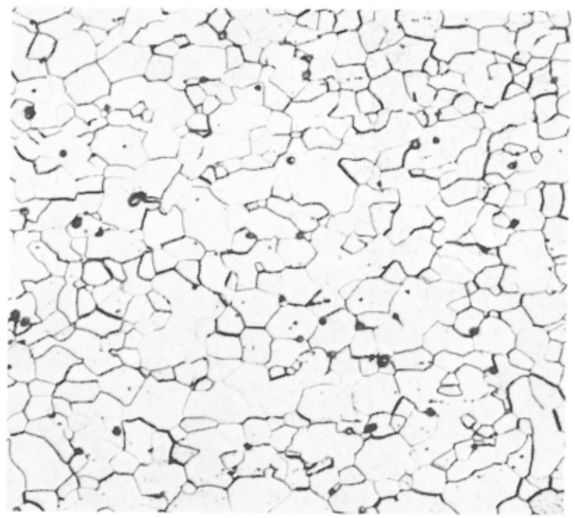


Fig. 42 Muffler-grade type 409 stainless steel (0.045C-11Cr-0.50Ti) strip, annealed 1 h per inch of thickness at 870 °C (1600 °F) and air cooled to RT. Equiaxed ferrite grains and dispersed titanium carbide particles. 10 mL HNO_3, 10 mL acetic acid, 15 mL HCl, and 2 drops glycerol. 100×

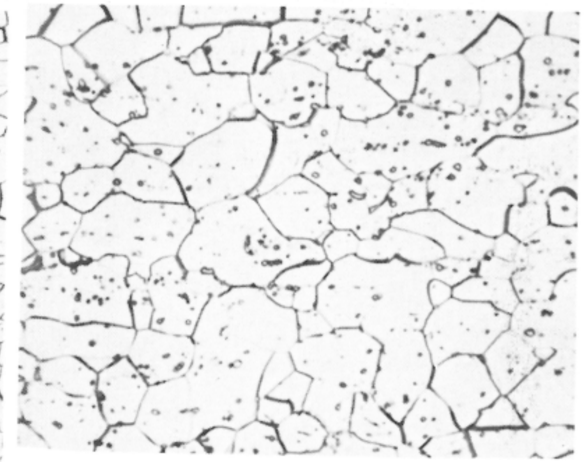


Fig. 43 Type 430 stainless steel strip, annealed at 845 °C (1550 °F) and cooled in air. The structure consists of equiaxed ferrite grains and randomly dispersed chromium carbide particles. Vilella's reagent. 500×

Typical Martensitic SS Microstructures

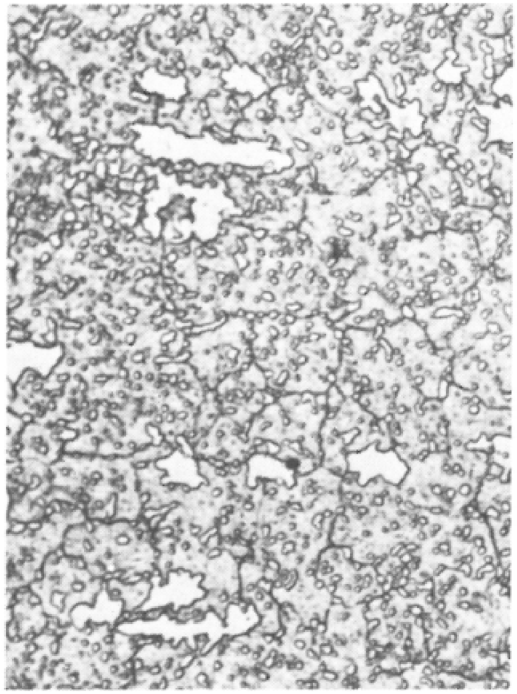


Fig. 63 Type 440C stainless steel bar, preheated 30 min at 760 °C (1400 °F), austenitized 30 min at 1025 °C (1875 °F), air cooled to 65 °C (150 °F), and double tempered (2 h each) at 425 °C (800 °F). Primary and secondary carbides (islands and particles) in tempered martensite. Superpicral. 500×

- "Spheroidize" anneal required for machining
- Fine carbides are for wear resistance, but large primary carbides can crack and cause fracture problems

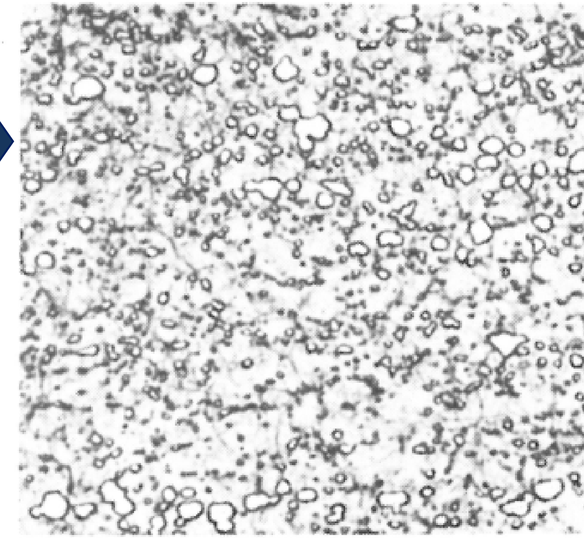


Fig. 58 Type 440A stainless steel, austenitized 30 min at 1010 °C (1850 °F), air cooled and tempered 30 min at 595 °C (1100 °F). The structure is partly spheroidized particles of chromium carbide in a martensitic matrix. Compare with the annealed structure shown in Fig. 57. 1% picric acid and 5% HCl in alcohol. 500×

Typical PH Stainless Steel Microstructures

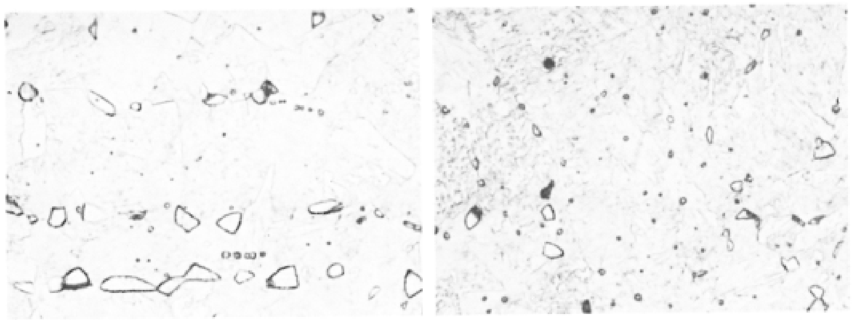


Fig. 75, 76 17-7PH semiaustenitic precipitation-hardenable stainless steel (165 HV) that was hot rolled and annealed. The outlined particles shown in this photomicrograph are δ-ferrite. Fig. 75: a longitudinal section. Fig. 76: a transverse section. Figures 77 and 78 show this alloy in the solution-annealed/air-cooled condition. Figure 79 illustrates a heat-treated, cold-rolled structure. Vilella's reagent. 1000×

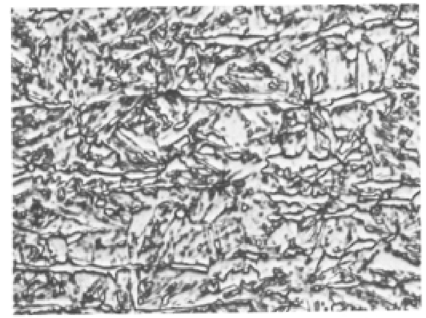
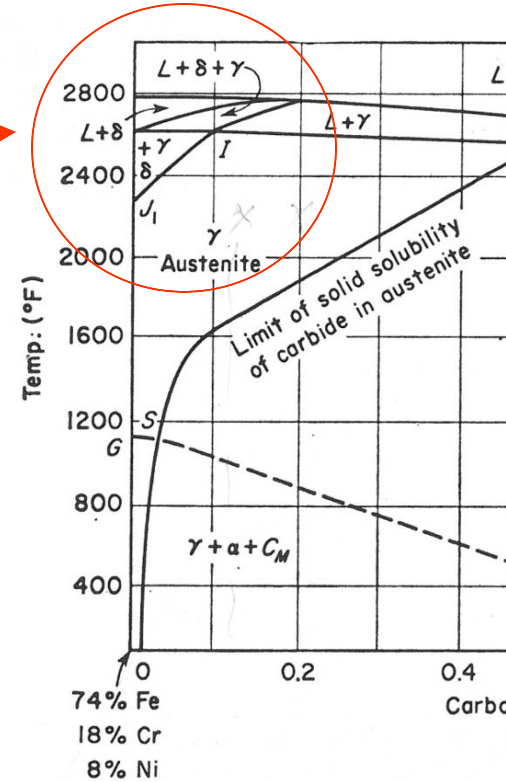


Fig. 77 17-7PH stainless, solution annealed at 1065 °C (1950 °F), then held 10 min at 955 °C (1750 °F), air cooled, held 8 h at −75 °C (−100 °F), held 1 h at 510 °C (950 °F), and air cooled. Ferrite stringers in a martensitic matrix. Vilella's reagent. 1000×



- Delta (δ)-ferrite often found
- Differing matrices
  - Austenite, martensite, semiaustenitic
  - Annealed versus hardened
  - Precipitates
    - Formed by solution treating & aging
    - Can't see without electron microscope

High Temperature Effects

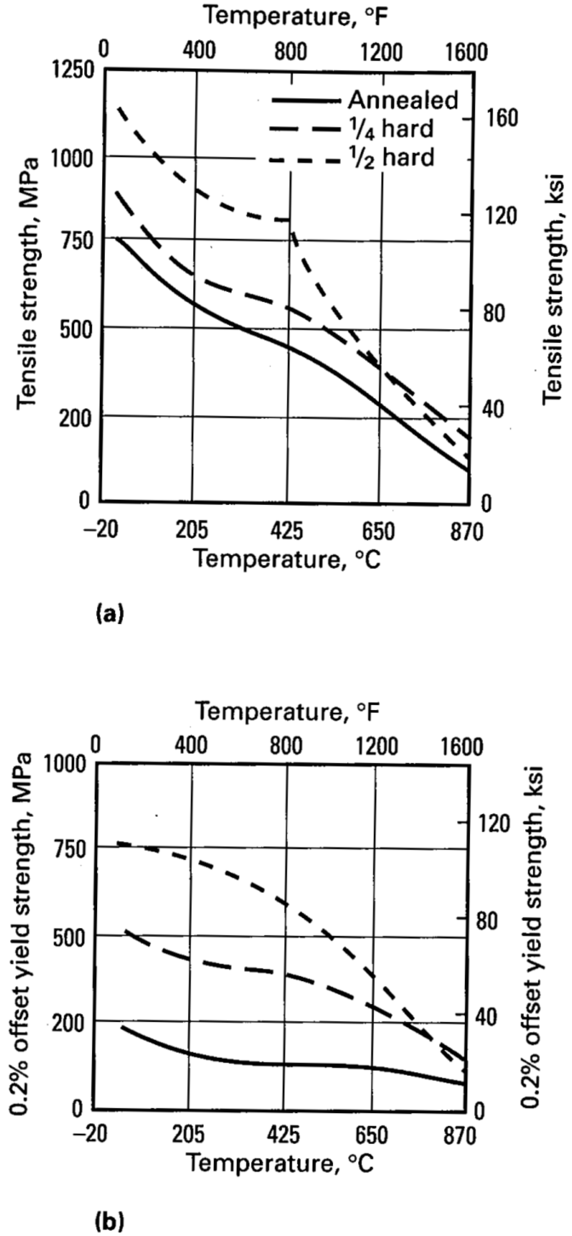
- Properties of materials with increasing temperature

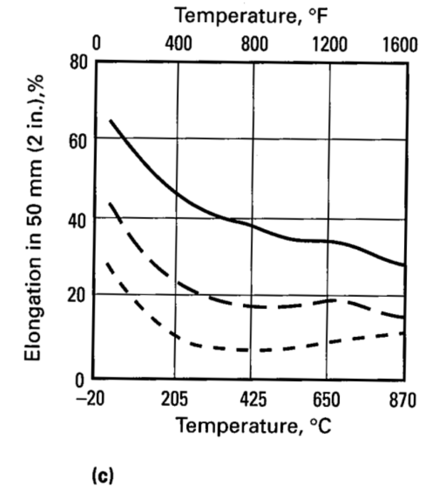
- Comparison of carbon and alloy steels to stainless steels

- Effect of Thermal Expansion Mismatch

Elevated Temperature Tensile Properties

- Strength almost always decreases with increasing T
- Ductility increases with increasing T with most metals, but not with austenitic stainless steels





:ig. 2 Effect of short-term elevated temperature on tensile properties of cold-worked 301 stain- ess steel. (a) Tensile strength. (b) Yield strength. (c) :longation

High temperature strength and corrosion resistance

- Ranking in order of increasing corrosion resistance
  - Carbon steel
  - Low alloy steel
  - Ferritic stainless steel
  - Austenitic stainless steel
- Same essential ranking as a function of high temperature strength

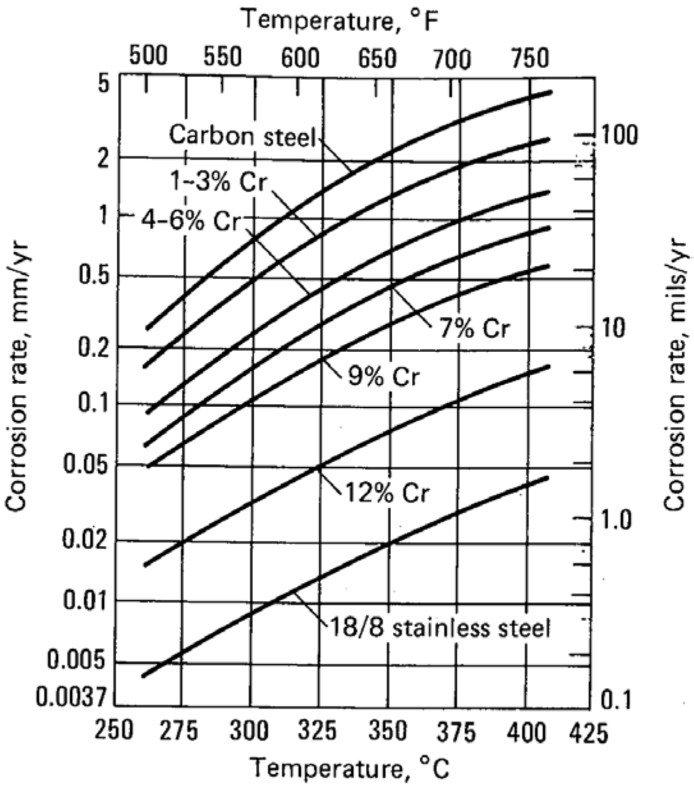
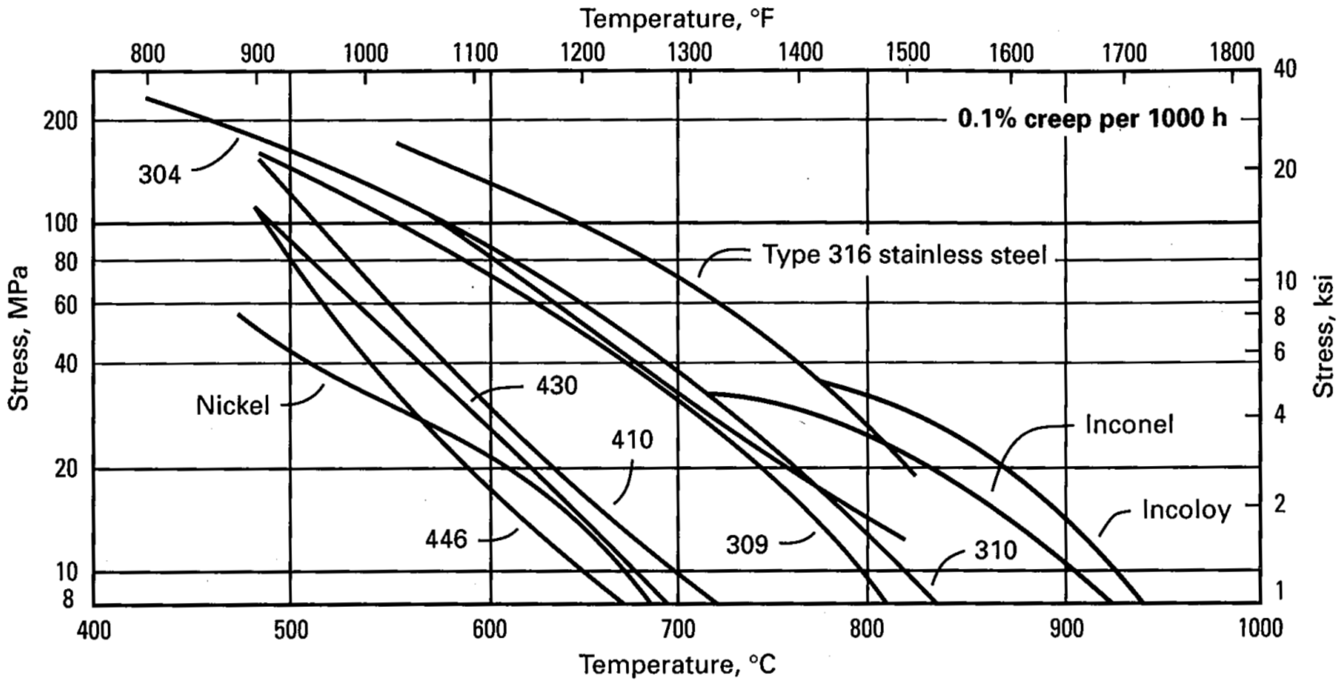


Fig. 10 Average high-temperature sulfur corrosion rates in a hydrogen-free environment compiled from an American Petroleum Institute survey. Source: Ref 19

Creep Resistance

- Creep is defined as strain that accumulates when a stress is applied to a heated material
- The metal elongates, sags, bulges, etc. over time
- Cracks form and fracture may eventually occur
- Austenitic stainless steels and nickel alloys can withstand higher temperatures or greater stress at temperature than ferritic stainless steels



Thermal Expansion Mismatch

- Strain = Thermal Expansion Coefficient x Temperature Difference
- $\varepsilon = \alpha * \Delta T$
- Consider alloys with two different values of alpha
- They are attached such that one material constrains the other when heated or cooled
- Strain, and thus stress, will accumulate in the material with lower thermal expansion
- Cracking or deformation can result, e.g., spalled coatings

Metal Alloy	Thermal Expansion Coefficient (microinch/inch/°F)
Aluminum 6061	13.0
Cartridge Brass (copper-30%zinc)	11.1
304 Stainless Steel	9.4
Plain carbon steel (1022)	6.5
Gray cast iron	5.7

What is a Failure

- ASM’s General Definition of a Failure:
  - “Failure” is a *general* term used to imply that a part in service
    1) Has become completely inoperable,
    2) Is still operable, but is incapable of satisfactorily performing its intended function, or
    3) Has deteriorated seriously, to the point that it has become unreliable or unsafe to use.

element™

Design Failure Causes or Contributions

- Design, manufacturing, and materials can all cause failures, either singly or in combination
- Choosing the wrong material is a design cause for failure
- Design failures are caused by not considering or inadequately handling the component's:
  - Loading
  - Constraint
  - Service environment (for temperature, corrosivity, or wind)
  - Actual usage conditions
  - Cyclic loading
  - Deleterious mechanical interaction with nearby components (abrasion due to dissimilar hardness)
  - Deleterious corrosion interaction with nearby components (galvanic interaction of two elements on different sides of the periodic table)

Failure Causes or Contributions from Manufacturing

- Defects produced by component manufacturing including surface roughness, nicks, sharp corners, poor tolerancing, dimensional agreement (fit), improper property specification, etc.

- Insufficient robustness
  - Low process repeatability and/or reproducibility, or
  - Unrepeatable or nonreproducible material response to a robust process.

- Insufficient quality assurance testing of production components due to
  - High cost
  - Inadequate available time, or
  - Almost as often, poorly specified test procedure or pass/fail criteria

Manufacturing Causes for Failures in All Metals (Materials)

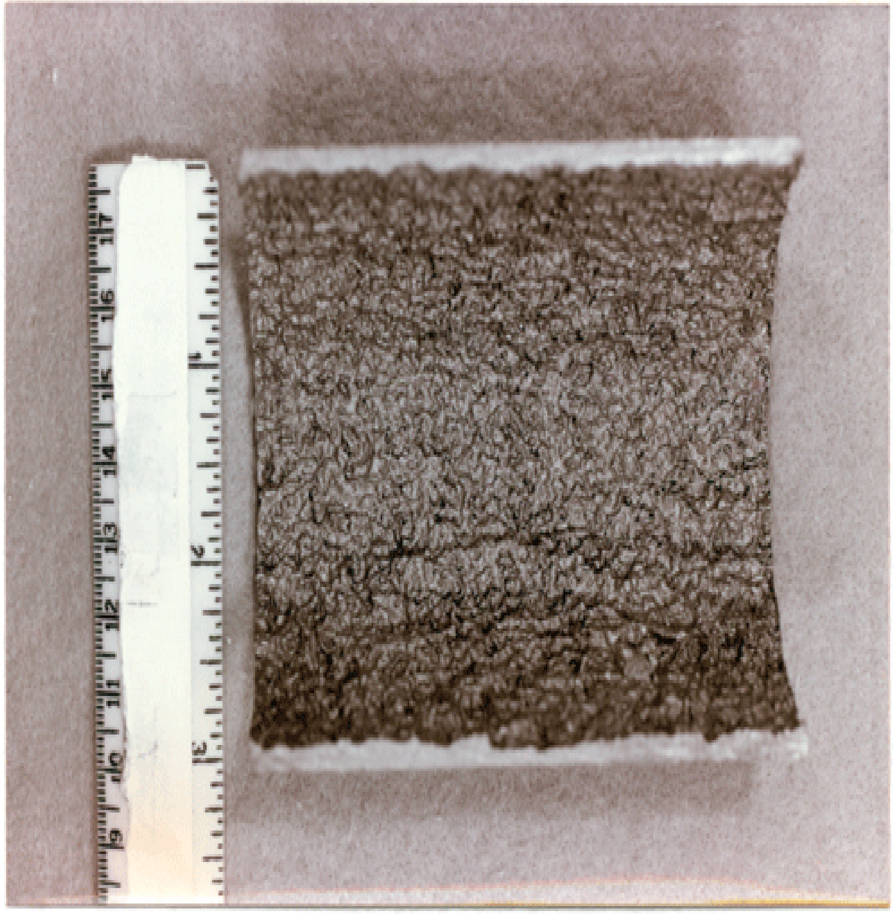
- Improper Composition
  - Incorrect concentration(s) of intended alloying element(s)
    - Throughout the structure
    - In certain locations (segregation)
  - Elevated residual element content
    - Could be desirable in some alloys, but not in this one
  - Elevated tramp element content
    - Impurity elements that are usually undesirable in alloys
- Grain size
  - Finer grain size is the only structural change that simultaneously increases strength and ductility
  - Large grain size is only desirable for creep resistance
- Elevated inclusion content or size:
  - Indigenous inclusions are native to the material or material source.
  - Exogenous inclusions are inadvertently added to the material.
- Improper condition of intentional surface layer
  - Out-of-specification thickness
  - Out of specification composition
- Improper heat treatment or thermal exposure
  - Decarburized
  - Carburized too deep or through-wall
  - Matrix is too hard or too soft
  - Undesirable brittle phase formation
  - Residual stress
- Intergranular networks

Materials Failure Mechanisms
(red color = applicable to Gas Engineering)

- Mechanical-Monotonic Overload
  - Tensile
  - Compression
  - Bending
  - Shear
    - Single
    - Double
  - Torsion
- Time-Dependent & Cyclic
  - Fatigue
  - Creep
  - Creep-Fatigue
- Temperature
  - Ductile-to-Brittle Transition
  - Differential Thermal Expansion
- Environmental
  - Corrosion
    - Galvanic
    - Fretting
    - Crevice
    - Pitting
    - Erosion
  - Combined Stress & Environmental
    - Stress Corrosion
    - Corrosion Fatigue
  - Embrittlement
    - Hydrogen
    - Liquid Metal
    - Solid Metal
    - Temper
    - Tempered Martensite
    - Aluminum Nitride
  - Wear
    - Galling
    - Abrasive
  - Oxidation

Uniform Corrosion

- Corrosion occurs evenly over a large surface area.
  - Example: CO_2 corrosion in a crude oil pipeline
- Corrosion rate increases by a factor of two for every 10°C increase in temperature

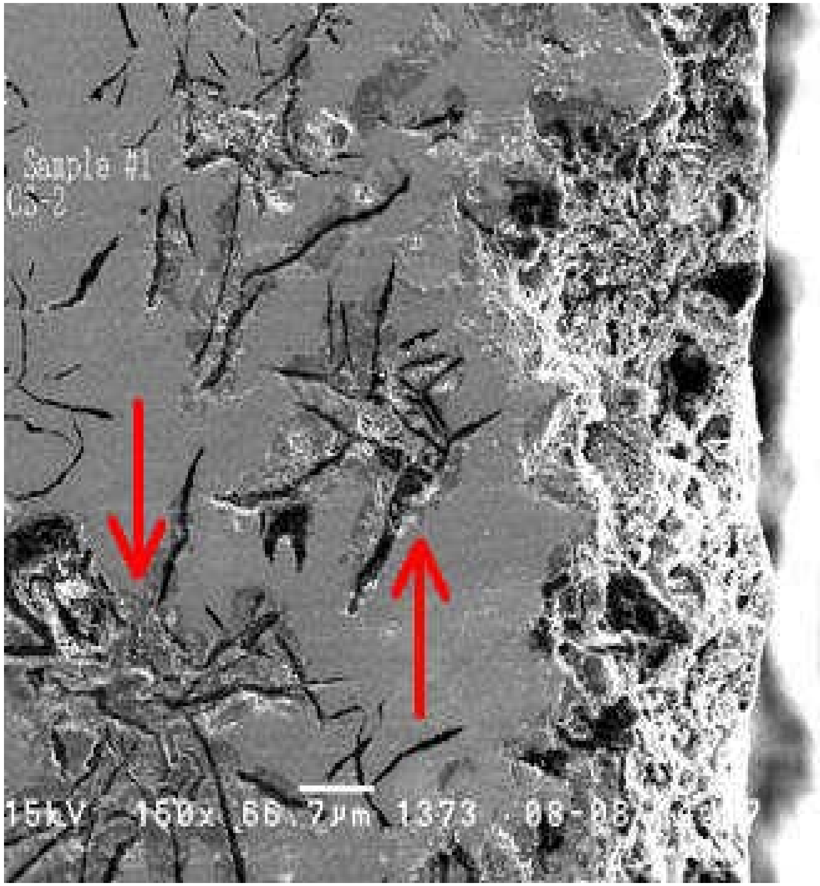


Uniform Corrosion

- **Galvanic corrosion is uniform corrosion**

  Example: Potable Water pipe (Cathode = Graphite; Anode = Gray or Ductile Cast Iron). Caused a Loss of mechanical strength.

- **3 Requirements**
  - –Dissimilar metals or alloys
  - –Dissimilar phases
  - –Conductive medium
  - –Electrical contact (Flow of electrons)



Uniform Corrosion: Galvanic Series in Seawater

- Magnesium
- Magnesium alloys
- Zinc
- Aluminum alloys
- Tin
- Stainless steel 430
- Lead
- 1010 Steel
- Cast Iron
- Copper
- Nickel
- Austenitic stainless steel 304
- Martensitic stainless steel 410
- 17-7 PH stainless steel
- Bronze
- Copper
- Red Brass
- Titanium 6Al-4V
- Silver
- Gold
- Graphite

- Anodic (More active)

↓

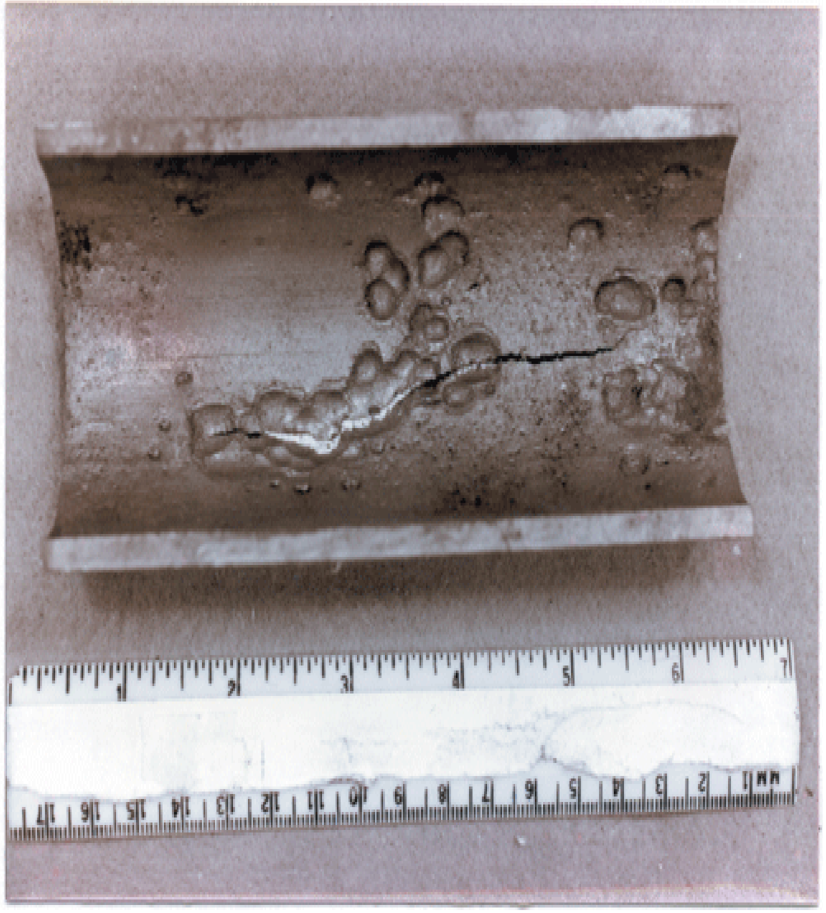
- Cathodic (Less Active)

Uniform Corrosion

- **Galvanic Series Guidelines**
  - Distance apart in the series
    - **Closer means Less Corrosion**
  - Small area (Cathode/Anode) ratio
    - **Small CAR is desirable**
  - Electrolyte is important
    - **Order of the cathodic versus anodic materials may change in different electrolytes**

Localized Corrosion: Pitting (Type 1)

- Localized corrosion occurs unevenly over a small surface area.
  - **Pitting is localized corrosion**: Formation of cavities or holes in a material
  - Pits are easily covered by protective film or corrosion products
  - Pits can be deep, but are wide at the top and narrow at the bottom
  - **Example:** Corrosion in a crude oil pipeline.



Localized Corrosion: Crevice (Type 2)

- **Crevice Corrosion is localized corrosion:**
  - –Corrosion between surfaces (that are covered up)
  - **Example: Crevice corrosion (beneath a seal) on a stainless steel flange exposed to a chloride medium**
- Similar to Pitting Corrosion
  - –Initiation
    - Chemical attack
      - – Electrolyte
      - – 0.10 – 100 μm between surfaces
      - – Contaminants & Stagnancy
  - –Properties
    - Increased damage with narrow gaps that run over a long distance
    - Pit can initiate it
    - Contact geometry is important

Environmentally-Induced Cracking

- Requires a combination of
  - Stress (applied or residual)
  - Corrosive medium, and
  - Susceptible material/condition
- Hydrogen Damage
- Stress Corrosion Cracking
- Liquid Metal Embrittlement

Stress Corrosion Cracking (SCC)

- Tensile Stress
  - Slow environmentally induced crack initiation and propagation in a corrosive medium (Delayed Failure Process)
    - 3 Stages
      - Crack Initiation
      - Crack Propagation
      - Failure
  - Cracks are often branched
  - Sulfur and chlorine environments cause SCC in many metals

Questions answered by “Fracture Analysis”

- The questions are:
  - How did ____ happen?
    - Correct substitutions for the underline are…..
      - the fracture
      - the crack
  - “What does the fracture or crack look like?” a.k.a.
    - What loading states were present? (Bending, tension, fatigue)
    - What was the fracture “morphology”? (Dimples, striations, cleavage)
    - Where did the crack “initiate”? (Fillet radius, sharp corner)
    - Can you see any feature that initiated the crack? (Nah, not always….better question is “Can you see, and then at least characterize, any feature that is present where the crack initiated?”)
    - How did the crack “propagate” (increase in length or branch through the material)?

Questions answered by "Failure Analysis"

- *Note that <u>some failures don't</u> include fractures, although <u>most failures do</u> include fractures. When the failure does include a fracture, the failure analysis also answers the previously stated questions answered by fracture analysis.*

- Additional correct questions answered by a failure analysis are:
  - *What* caused the failure?
  - *When* did the failure happen? (Not in time sense, but in process sequence.)
  - Is the failed component different than the rest of the components in inventory or service?
  - *Who* is responsible for the failure?

Typical Stages Of A Failure Analysis

- Gather Information
- Nondestructive Testing
- Destructive Testing
- Reporting

Get Part Information

- Identification information
- Material composition
- Applicable specifications and/or drawings
- Heat treatment
- Mechanical properties
- Physical characteristics
- Manufacturing process steps
- Relationship to other components when in use

Get Part History

- Service duration and storage
- Operating Environment – elevated temperature or corrosive exposure
- Types of loading - tension, compressive, torsion, cyclic, impact
- Anomalous service conditions
- Failure of adjacent components
- Repair and rework history
- Frequency of occurrence of other failures

Sampling and Testing Plan

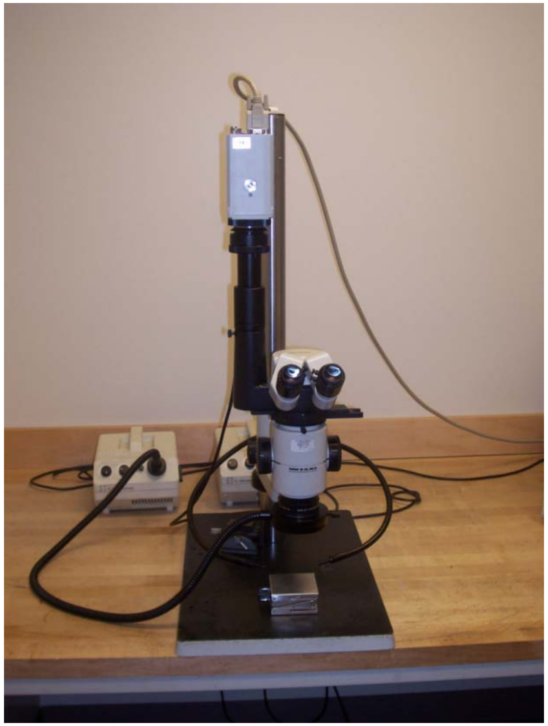
- Collect and preserve information and physical Items
- Determine the scope of investigation
- Define timing for completion
- Plan sequence of examinations for the failed item
  - Other examples (“exemplars”) available for study?
- Prepare a test protocol

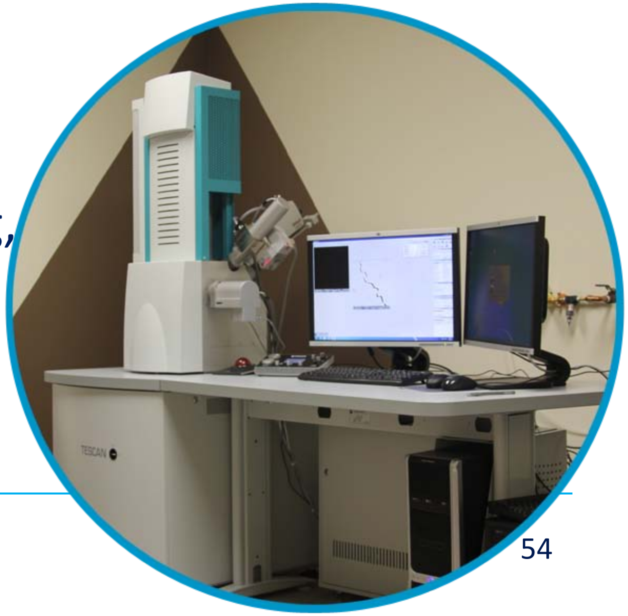
Perform a Material Evaluation

- Document materials and components
- Mechanical testing
- Chemical analysis
- Metallography
- Fractography by optical and scanning electron microscopy
  - Utilize replicas for samples that are too large or cannot be cut
- Environmental testing (rarely but sometimes used)
- Special testing
  - Examples: dimensional measurements, surface roughness measurement, accident reconstruction, finite element analysis, simulation
  - Usually in the realm of mechanical engineering

Fractography

- **Fractography is the pictorial evaluation of a fracture surface**
  - **Optical to magnifications of 60 X**
  - **Scanning electron microscopy (SEM) at magnifications to about 50,000X including localized chemical analysis by energy dispersive spectroscopy (EDS)**
- **Fractography is required** in failure analyses **to determine *how* a part fractured**:
  - What types of loading were operative: tensile, shear, bending, torsion, fatigue (axial tension-tension, unidirectional bending, reversed bending, rotational bending, torsion)?
  - Where did cracking initiate and what part of the component fractured last?





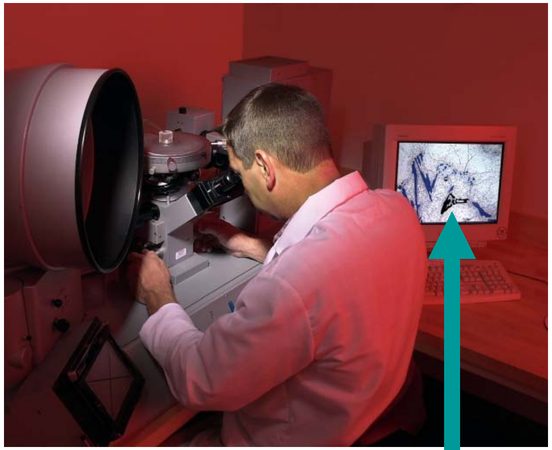
Mechanical Testing (MT) That Is Frequently Used

- Compare all results to
  - Specification
  - Expectations
- Hardness testing
  - Brinell, Rockwell, Vickers
- Microhardness testing
  - Usually on metallographic mount
  - Knoop or Vickers
- Tensile testing
  - Report UTS, YS, %El, %RA

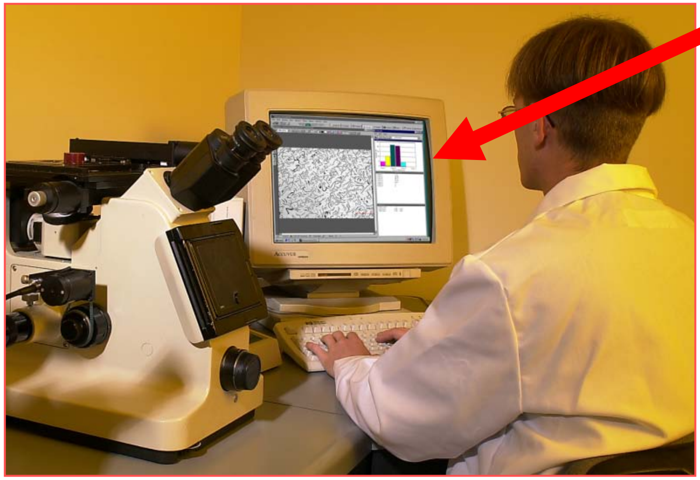
Chemical Analysis:
Listed in Order of Frequency of Usage

1. Optical and glow discharge optical emission spectroscopy
   – Solid state; OES & GD-OES
2. Combustometric "LECO" testing
   – Gaseous state; exclusively for carbon, sulfur, oxygen, nitrogen and hydrogen
   – Cannot be conducted on alloys with low melting points (aluminum and magnesium)
3. Inductively Coupled Plasma Emission Spectroscopy (ICP)
   – Conducted in liquid state for standards and unknown solutions
4. Energy Dispersive Spectroscopy (EDS)
   – Analyze base material or deposits
   – Conducted on a scanning electron microscope (SEM)
5. X-ray Diffraction (XRD)
   – Gives crystal structure
   – Must be combined with other elemental techniques
6. Organic Analysis Methods (FTIR, DSC, TGA, GC)

Metallography



- Purpose: Evaluate correlation of fracture or corrosion with microstructure
- Section
- Mount
- Polish
- Etch



- Qualitative: photograph with a “metallograph”
- Quantitative Image Analysis
  - Statistics on volume fraction or size of particles and inclusions

Why is this all important?

- Stainless steels are key alloys for gas engineers
- With this seminar, we've discussed "structure" and "properties" which are two of the central elements of MSE

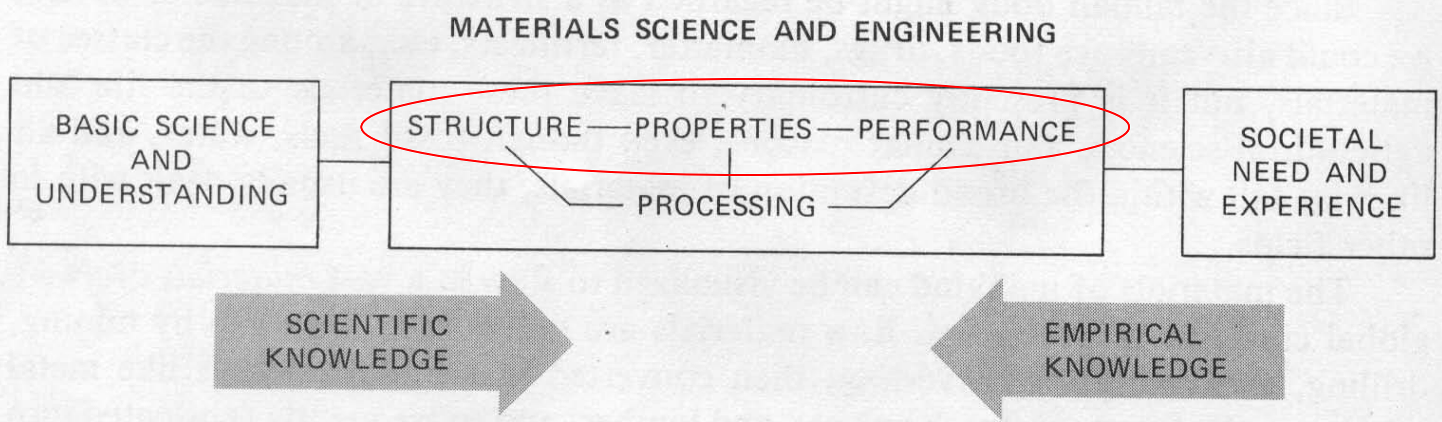


Fig. I A representation of the central elements of MSE, in relation to the countercurrent flows of scientific and empirical knowledge.

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