Mechanical Engineering Design (Design I)

Content:

1. Simple stresses and material selection.
2. Combined stresses.
3. Dynamic loading design.
4. Shafts and Forces on belts and Gears.
5. Keys, splines & couplings.
6. Rolling bearings selection.
7. Clutches and brakes.
8. Power screws, bolts and welding.
9. Pressure vessels.
10. Gears and belts

References:

1. Machine Elements in Mechanical Design by Robert L. Mott, P.E.
2. Mechanical Engineering Design by Shigley.
3. Machine Elements by Gustav Niemann.
4. Machine Design by Gupta.
5. Machine Design by Black and Adams.

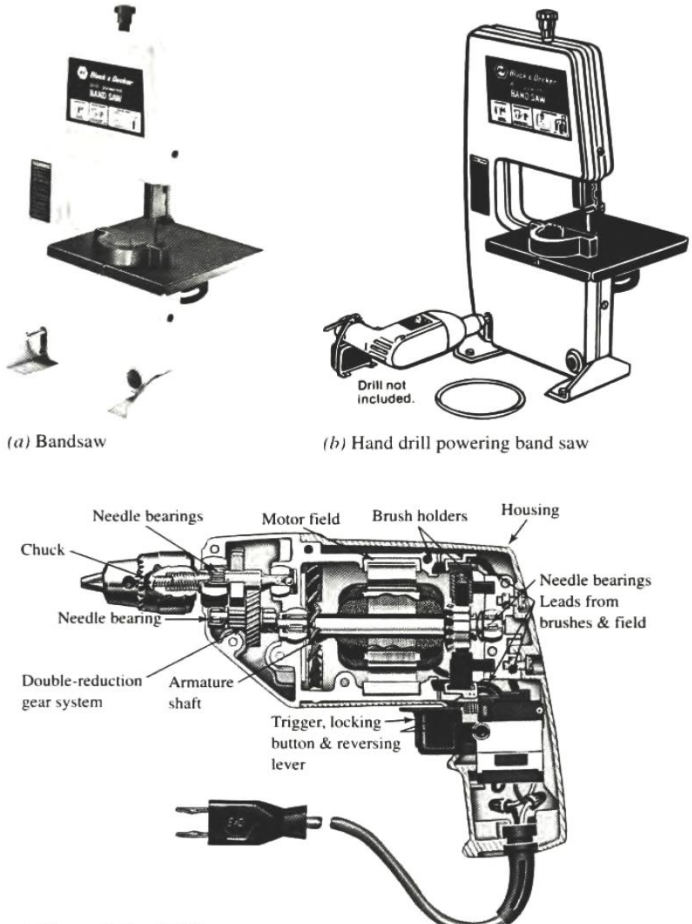
LECTURE ONE & TWO

The Nature of Mechanical Design and Materials in Mechanical Design

(Note: See chapter 1 & 2 of Reference No.1)

There are many fields where mechanical products are designed and produced. For examples see figures (1-1 to 1-10).

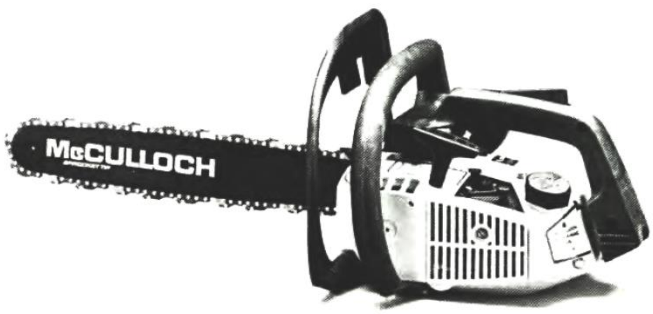
FIGURE 1–1 Drill-powered band saw [Courtesy of Black & Decker (U.S.) Inc.]

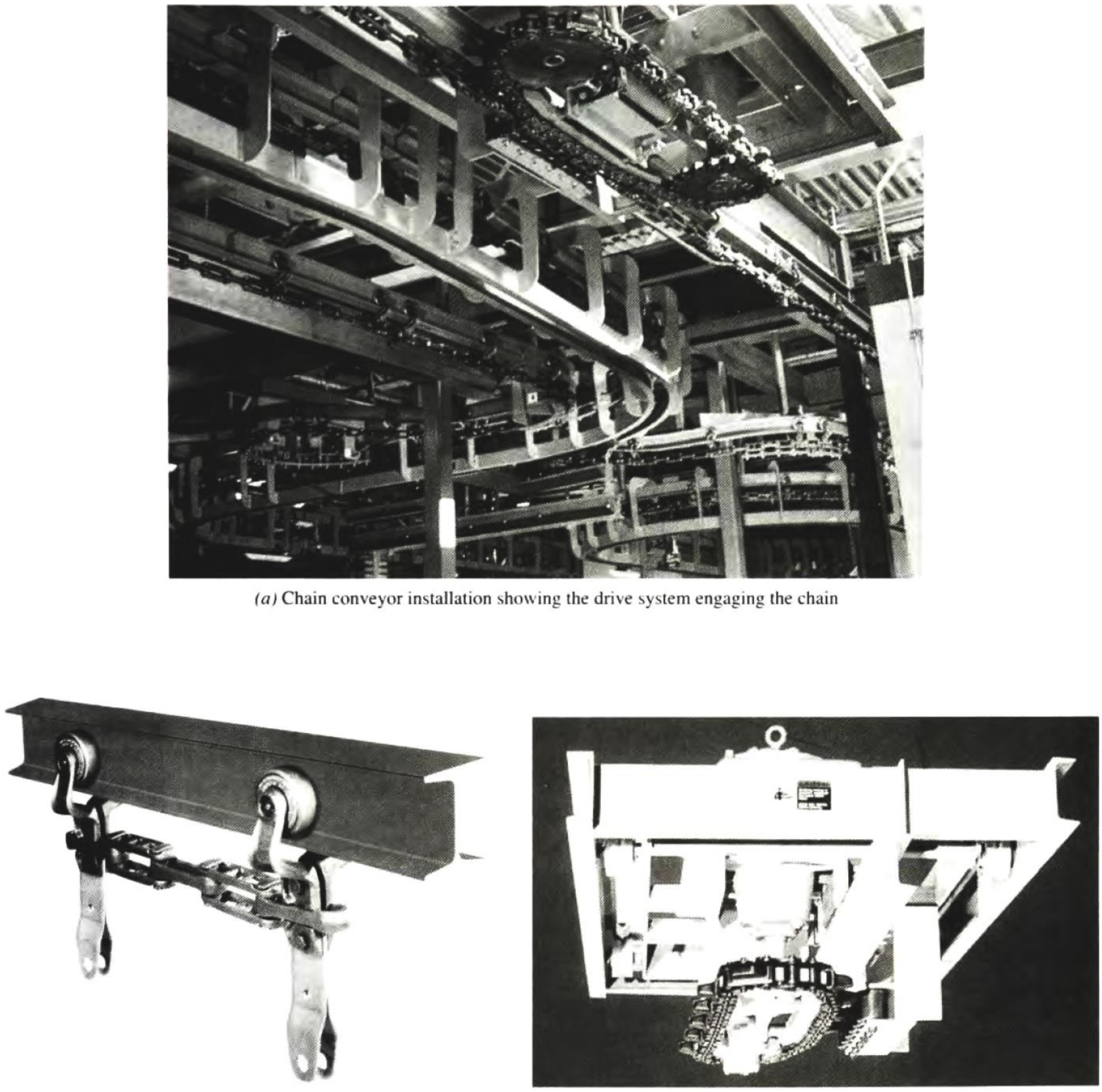


(a) Bandsaw (b) Hand drill powering band saw

(c) Parts of a hand drill

FIGURE 1–2 Chain saw (Copyright McCulloch Corporation, Los Angeles, CA)



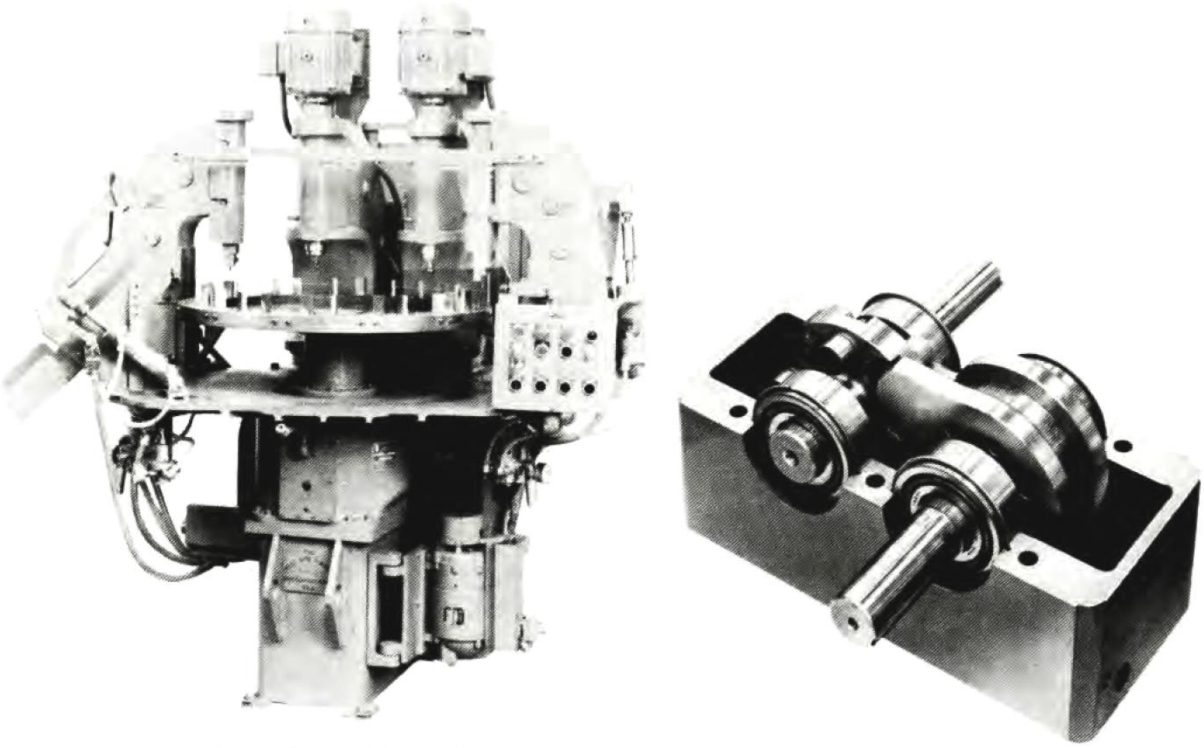


(a) Chain conveyor installation showing the drive system engaging the chain

(b) Chain and roller system supported on an I-beam

(c) Detail of the drive system and its structure

FIGURE 1–3 Chain conveyor system (Richards-Wilcox, Inc., Aurora, IL)



(a) Automatic assembly machine with indexing table

(b) Indexing drive mechanism

FIGURE 1–4 Machinery to automatically assemble automotive components (Industrial Motion Control, LLC, Wheeling, IL)

FIGURE 1–5 Industrial crane (Air Technical Industries, Mentor, OH)

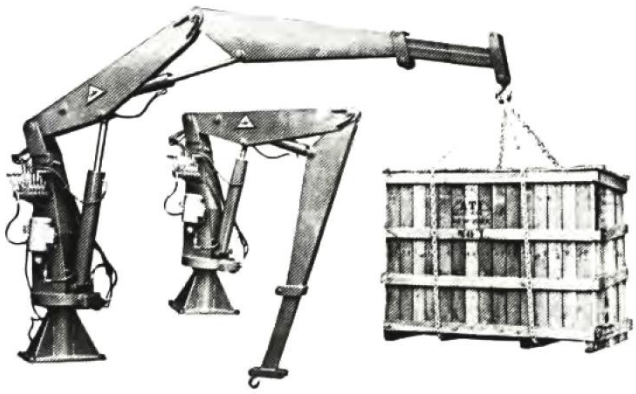
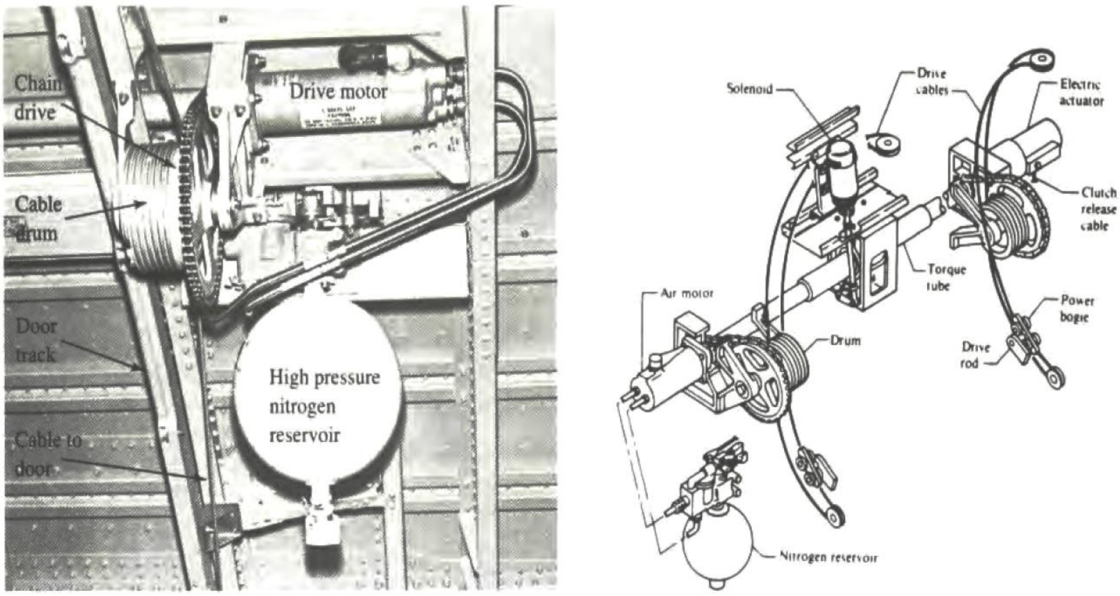


FIGURE 1–6 Tractor with a front-end-loader attachment (Case IH, Racine, WI)

FIGURE 1–7 Tractor pulling an implement (Case IH, Racine, WI)

FIGURE 1–8 Cutaway of a tractor (Case IH, Racine, WI)



(a) Photograph of installed mechanism *(b)* Cabin door drive mechanism

FIGURE 1–9 Aircraft door drive mechanism (The Boeing Company, Seattle, WA)

FIGURE 1–10
Aircraft landing gear assembly (The Boeing Company, Seattle, WA)

Machine elements must be compatible, must fit well together and must perform safely and efficiently. Figure (1-12) shows and example for the primary elements of the speed reducer, which consists: Gear, Shafts, Bearings, Keys, Housing and you can add many other items.

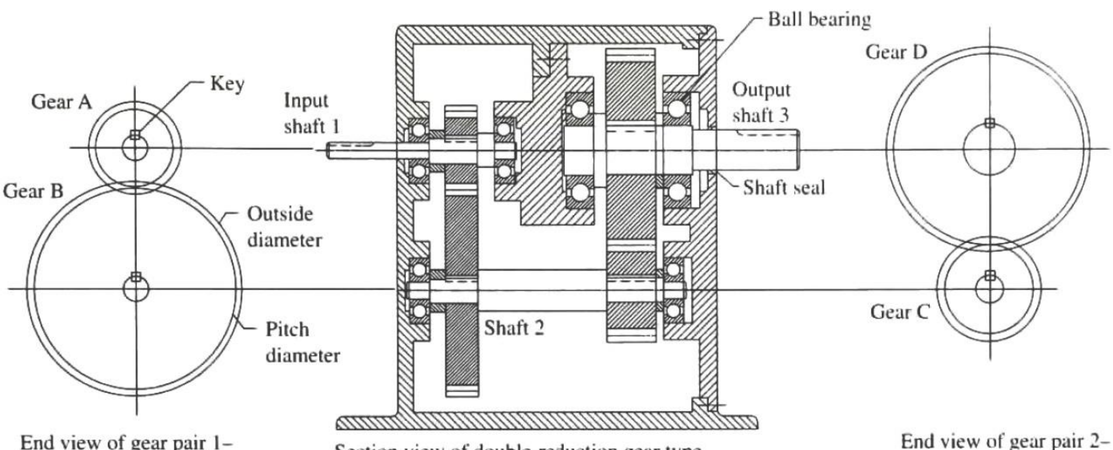
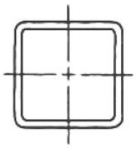
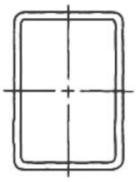


FIGURE 1–12 Conceptual design for a speed reducer

Steel structural shapes

Table (1-1 Page 21) shows standard angle (L-shapes) channels (C-shapes), etc. See Appendix 16; page (A-31 to A-38).

TABLE 1–1 Designations for steel and aluminum shapes

Name of shape	Shape	Symbol	Example designation and Appendix table
Angle		L	$L4 \times 3 \times \frac{1}{2}$ Table A16–1
Channel		C	$C15 \times 50$ Table A16–2
Wide-flange beam		W	$W14 \times 43$ Table A16–3
American Standard beam		S	$S10 \times 35$ Table A16–4
Structural tubing—square			$4 \times 4 \times \frac{1}{4}$ Table A16–5
Structural tubing—rectangular			$6 \times 4 \times \frac{1}{4}$ Table A16–5
Pipe			4-inch standard weight 4-inch Schedule 40 Table A16–6
Aluminum Association channel		C	$C4 \times 1.738$ Table A17–1
Aluminum Association I-beam		I	$I8 \times 6.181$ Table A17–2

Unit systems:

Table (A18-1) and (18-2) page A-39 shows conversation of U.S customary units to SI units.

Note: you should work with SI unit always.

APPENDIX 18 CONVERSION FACTORS

TABLE A18–1 Conversion of U.S. Customary units to SI units: basic quantities

Quantity	U.S. Customary unit		SI unit		Symbol	Equivalent units
Length	1 foot (ft)	=	0.3048	meter	m	
Mass	1 slug	=	14.59	kilogram	kg	
Time	1 second	=	1.0	second	s	
Force	1 pound (lb)	=	4.448	newton	N	$kg \cdot m/s^2$
Pressure	1 lb/in^2	=	6895	pascal	Pa	N/m^2 or $kg/m \cdot s^2$
Energy	1 ft-lb	=	1.356	joule	J	$N \cdot m$ or $kg \cdot m^2/s^2$
Power	1 ft-lb/s	=	1.356	watt	W	J/s

TABLE A18–2 Other convenient conversion factors

Length	1 ft	=	0.3048	m
	1 in	=	25.4	mm
	1 mi	=	5280	ft
	1 mi	=	1.609	km
	1 km	=	1000	m
	1 cm	=	10	mm
	1 m	=	1000	mm
Area	1 ft^2	=	0.0929	m^2
	1 in^2	=	645.2	mm^2
	1 m^2	=	10.76	ft^2
	1 m^2	=	10^6	mm^2
Volume	1 ft^3	=	7.48	gal
	1 ft^3	=	1728	in^3
	1 ft^3	=	0.0283	m^3
	1 gal	=	0.00379	m^3
	1 gal	=	3.785	L
	1 m^3	=	1000	L
Volume flow rate	1 ft^3/s	=	449	gal/min
	1 ft^3/s	=	0.0283	m^3/s
	1 gal/min	=	6.309×10^{-5}	m^3/s
	1 gal/min	=	3.785	L/min
	1 L/min	=	16.67×10^{-6}	m^3/s

Stress, pressure, or unit loading	1 lb/in^2	=	6.895	kPa
	1 lb/ft^2	=	0.0479	kPa
	1 kip/in^2	=	6.895	MPa
Section modulus	1 in^3	=	1.639×10^4	mm^3
Moment of inertia	1 in^4	=	4.162×10^5	mm^4
Density	1 $slug/ft^3$	=	515.4	kg/m^3
Specific weight	1 lb/ft^3	=	157.1	N/m^3
Energy	1 ft·lb	=	1.356	J
	1 Btu	=	1.055	kJ
	1 W·h	=	3.600	kJ
Torque or moment	1 lb·in	=	0.1130	N·m
Power	1 hp	=	550	ft·lb/s
	1 hp	=	745.7	W
	1 ft·lb/s	=	1.356	W
	1 Btu/h	=	0.293	W
Temperature	$T(°C)$	=	$[T(°F) - 32]5/9$	
	$T(°F)$	=	$\frac{9}{5}[T(°C)] + 32$	

Example 1 (page 26), Ref.1:

Express the diameter of a shaft in (mm) if it is measured to be 2.755 in.

Sol:

Table A18 gives the conversation factor for length to be (1 in = 25.4 mm) then

$$Diameter = 2.755\ in * \frac{25.4\ mm}{1\ in} = 69.98\ mm$$

Note: see also example 1-2 page 26 (Solve problems on page 28 Prob. 15-16-17-18-19-20-22-23-25-26-28)

Materials in Mechanical Design:

- **Tensile Strength, S_u**

The peak of the stress-strain curve is considered the ultimate tensile strength (S_U) sometimes called the ultimate strength or simply the tensile strength. At this point during the test, the highest apparent stress on a test bar of the material is measured. As shown in Figures 2-1 and 2-2. The curve appears to drop off after the peak. However, notice that the instrumentation used to create the diagrams is actually plotting load versus deflection rather than true stress versus strain. The apparent stress is computed by dividing the load by the original cross-sectional area of the test bar. After the peak of the curve is reached, there is a pro-nounced decrease in the bar's diameter, referred to as necking down. Thus, the load acts over a smaller area, and the actual stress continues to increase until failure. It is very difficult to follow the reduction in diameter during the necking-down process, so it has become cus-tomary to use the peak of the curve as the tensile strength, although it is a more conservative value.

- **Yield Strength, S_Y**

That portion of the stress-strain diagram where there is a large increase in strain with little or no increase in stress is called the yield strength (**S_Y**). This property indicates that the material has, in fact, yielded or elongated plastically, permanently, and to a large degree. If the point of yielding is quite noticeable, as it is in Figure 2-1, the property is called the yield point rather than the yield strength. This is typical of plain carbon hot rolled steel. Figure 2-2 shows the stress-strain diagram form that is typical of a nonferrous metal such as aluminum or titanium or of certain high-strength steels. Notice that there is no pro-nounced yield point, but the material has actually yielded at or near the

stress level indicated as S_Y. That point is determined by the offset method, in which a line is drawn parallel to the straight-line portion of the curve and is offset to the right by a set amount, usually 0.20% strain (0.002 in/in). The intersection of this line and the stress-strain curve defines the material's yield strength. In this book, the term yield strength will be used for S_Y regardless of whether the material exhibits a true yield point or whether the offset method is used.

FIGURE 2–1 Typical stress-strain diagram for steel

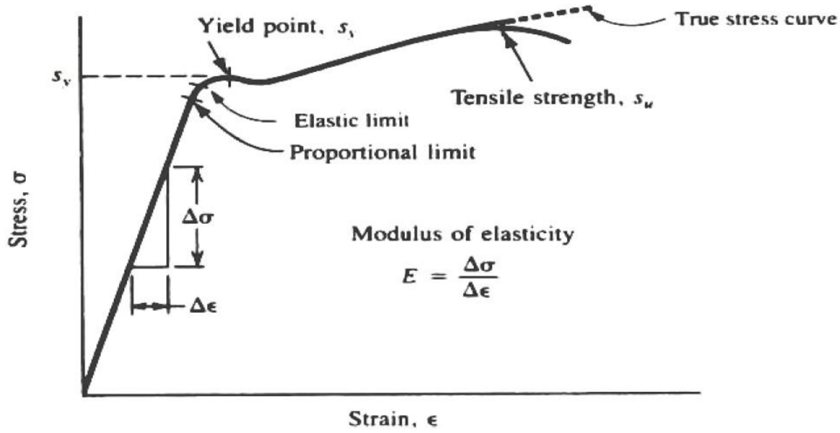
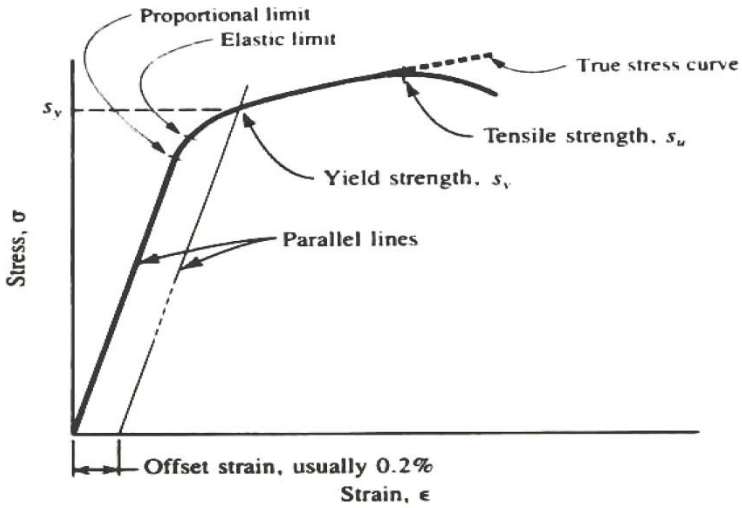


FIGURE 2–2 Typical stress-strain diagram for aluminum and other metals having no yield point



Where: S_u = ultimate tensile strength

S_Y = yield strength

E = modulus of Elasticity = $\frac{\sigma}{\epsilon}$

σ = stress

ϵ = strain

<u>For shear strength</u>

S_{YS} = yield strength in shear = $S_Y/2 = 0.5\ S_Y$

S_{US} = ultimate strength in shear = $0.75\ S_U$

Classification of metals and alloys

UNS : The Unified Numbering systems.

ASTM : The American Society for Testing and Materials

AA : The Aluminum Association.

AISI : The American Iron and Steel Institute.

CDA : The Copper Development Association.

SAE : The Society of Automotive Engineers.

Steel Designation System:

Section 2–5 ▪ Carbon and Alloy Steel

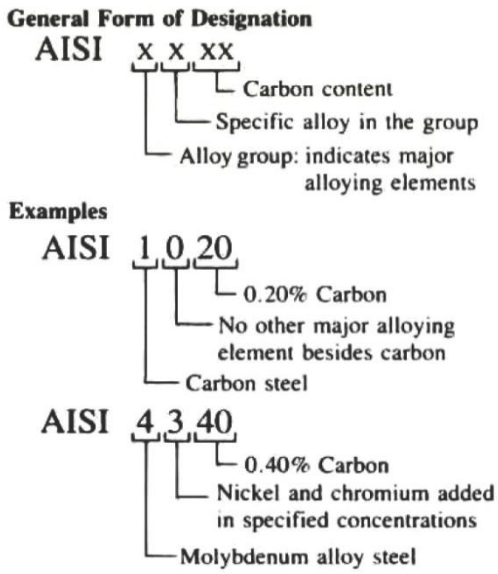


FIGURE 2–11 Steel designation system

Importance of Carbon:

As carbon content increase, strength and hardness also increased under the same conditions of processing and heat treatment. Since the ductility decreases with the increasing of carbon content, selecting suitable steel involves some compromise between strength and ductility.

As a rough classification scheme:

Low-carbon steel ≅ 0.3% carbon → (low strength + good formability)
Medium-carbon steel ≅ (0.3% - 0.5%) → (Moderate to high strength + fairly good ductility)
High-carbon steel ≅ (0.5% - 0.95%) → (suitable for durable cutting edges)

Properties of carburized steel, stainless steel, structural steel…

APPENDIX 3 DESIGN PROPERTIES OF CARBON AND ALLOY STEELS

Material designation (AISI number)	Condition	Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)	Brinell hardness (HB)
1020	Hot-rolled	55	379	30	207	25	111
1020	Cold-drawn	61	420	51	352	15	122
1020	Annealed	60	414	43	296	38	121
1040	Hot-rolled	72	496	42	290	18	144
1040	Cold-drawn	80	552	71	490	12	160
1040	OQT 1300	88	607	61	421	33	183
1040	OQT 400	113	779	87	600	19	262
1050	Hot-rolled	90	620	49	338	15	180
1050	Cold-drawn	100	690	84	579	10	200
1050	OQT 1300	96	662	61	421	30	192
1050	OQT 400	143	986	110	758	10	321
1117	Hot-rolled	62	427	34	234	33	124
1117	Cold-drawn	69	476	51	352	20	138
1117	WQT 350	89	614	50	345	22	178
1137	Hot-rolled	88	607	48	331	15	176
1137	Cold-drawn	98	676	82	565	10	196
1137	OQT 1300	87	600	60	414	28	174
1137	OQT 400	157	1083	136	938	5	352
1144	Hot-rolled	94	648	51	352	15	188
1144	Cold-drawn	100	690	90	621	10	200
1144	OQT 1300	96	662	68	469	25	200
1144	OQT 400	127	876	91	627	16	277
1213	Hot-rolled	55	379	33	228	25	110
1213	Cold-drawn	75	517	58	340	10	150
12L13	Hot-rolled	57	393	34	234	22	114
12L13	Cold-drawn	70	483	60	414	10	140
1340	Annealed	102	703	63	434	26	207
1340	OQT 1300	100	690	75	517	25	235
1340	OQT 1000	144	993	132	910	17	363
1340	OQT 700	221	1520	197	1360	10	444
1340	OQT 400	285	1960	234	1610	8	578
3140	Annealed	95	655	67	462	25	187
3140	OQT 1300	115	792	94	648	23	233
3140	OQT 1000	152	1050	133	920	17	311
3140	OQT 700	220	1520	200	1380	13	461
3140	OQT 400	280	1930	248	1710	11	555
4130	Annealed	81	558	52	359	28	156
4130	WQT 1300	98	676	89	614	28	202
4130	WQT 1000	143	986	132	910	16	302
4130	WQT 700	208	1430	180	1240	13	415
4130	WQT 400	234	1610	197	1360	12	461
4140	Annealed	95	655	60	414	26	197
4140	OQT 1300	117	807	100	690	23	235
4140	OQT 1000	168	1160	152	1050	17	341
4140	OQT 700	231	1590	212	1460	13	461
4140	OQT 400	290	2000	251	1730	11	578

APPENDIX 5 PROPERTIES OF CARBURIZED STEELS

Material designation (AISI number)	Condition	Core properties: Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)	Brinell hardness (HB)	Case hardness (HRC)
1015	SWQT 350	106	731	60	414	15	217	62
1020	SWQT 350	129	889	72	496	11	255	62
1022	SWQT 350	135	931	75	517	14	262	62
1117	SWQT 350	125	862	66	455	10	235	65
1118	SWQT 350	144	993	90	621	13	285	61
4118	SOQT 300	143	986	93	641	17	293	62
4118	DOQT 300	126	869	63	434	21	241	62
4118	SOQT 450	138	952	89	614	17	277	56
4118	DOQT 450	120	827	63	434	22	229	56
4320	SOQT 300	218	1500	178	1230	13	429	62
4320	DOQT 300	151	1040	97	669	19	302	62
4320	SOQT 450	211	1450	173	1190	12	415	59
4320	DOQT 450	145	1000	94	648	21	293	59
4620	SOQT 300	119	820	83	572	19	277	62
4620	DOQT 300	122	841	77	531	22	248	62
4620	SOQT 450	115	793	80	552	20	248	59
4620	DOQT 450	115	793	77	531	22	235	59
4820	SOQT 300	207	1430	167	1150	13	415	61
4820	DOQT 300	204	1405	165	1140	13	415	60
4820	SOQT 450	205	1410	184	1270	13	415	57
4820	DOQT 450	196	1350	171	1180	13	401	56
8620	SOQT 300	188	1300	149	1030	11	388	64
8620	DOQT 300	133	917	83	572	20	269	64
8620	SOQT 450	167	1150	120	827	14	341	61
8620	DOQT 450	130	896	77	531	22	262	61
E9310	SOQT 300	173	1190	135	931	15	363	62
E9310	DOQT 300	174	1200	139	958	15	363	60
E9310	SOQT 450	168	1160	137	945	15	341	59
E9310	DOQT 450	169	1170	138	952	15	352	58

Notes: Properties given are for a single set of tests on 1/2-in round bars.

SWQT: single water-quenched and tempered

SOQT: single oil-quenched and tempered

DOQT: double oil-quenched and tempered

300 and 450 are the tempering temperatures in °F. Steel was carburized for 8 h. Case depth ranged from 0.045 to 0.075 in.

APPENDIX 6 PROPERTIES OF STAINLESS STEELS

Material designation			Tensile strength		Yield strength		Ductility (percent elongation
AISI number	UNS	Condition	(ksi)	(MPa)	(ksi)	(MPa)	in 2 inches)
Austenitic steels							
201	S20100	Annealed	115	793	55	379	55
		1/4 hard	125	862	75	517	20
		1/2 hard	150	1030	110	758	10
		3/4 hard	175	1210	135	931	5
		Full hard	185	1280	140	966	4
301	S30100	Annealed	110	758	40	276	60
		1/4 hard	125	862	75	517	25
		1/2 hard	150	1030	110	758	15
		3/4 hard	175	1210	135	931	12
		Full hard	185	1280	140	966	8
304	S30400	Annealed	85	586	35	241	60
310	S31000	Annealed	95	655	45	310	45
316	S31600	Annealed	80	552	30	207	60
Ferritic steels							
405	S40500	Annealed	70	483	40	276	30
430	S43000	Annealed	75	517	40	276	30
446	S44600	Annealed	80	552	50	345	25
Martensitic steels							
410	S41000	Annealed	75	517	40	276	30
416	S41600	Q&T 600	180	1240	140	966	15
		Q&T 1000	145	1000	115	793	20
		Q&T 1400	90	621	60	414	30
431	S43100	Q&T 600	195	1344	150	1034	15
440A	S44002	Q&T 600	280	1930	270	1860	3
Precipitation-hardening steels							
17-4PH	S17400	H 900	200	1380	185	1280	14
		H 1150	145	1000	125	862	19
17-7PH	S17700	RH 950	200	1380	175	1210	10
		TH 1050	175	1210	155	1070	12

APPENDIX 7 PROPERTIES OF STRUCTURAL STEELS

Material designation (ASTM number)	Grade, product, or thickness	Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)
A36	$t \le 8$ in	58	400	36	250	21
A242	$t \le 3/4$ in	70	480	50	345	21
A242	$t \le 1\frac{1}{2}$ in	67	460	46	315	21
A242	$t \le 4$ in	63	435	42	290	21
A500	Cold-formed structural tubing, round or shaped					
	Round, Grade A	45	310	33	228	25
	Round, Grade B	58	400	42	290	23
	Round, Grade C	62	427	46	317	21
	Shaped, Grade A	45	310	39	269	25
	Shaped, Grade B	58	400	46	317	23
	Shaped, Grade C	62	427	50	345	21
A501	Hot-formed structural tubing, round or shaped	58	400	36	250	23
A514	Quenched and tempered, $t \le 2\frac{1}{2}$ in	110–130	760–895	100	690	18%
A572	42, $t \le 6$ in	60	415	42	290	24
A572	50, $t \le 4$ in	65	450	50	345	21
A572	60, $t \le 1\frac{1}{4}$ in	75	520	60	415	18
A572	65, $t \le 1\frac{1}{4}$ in	80	550	65	450	17
A588	$t \le 4$ in	70	485	50	345	21
A992	W-shapes	65	450	50	345	21

Note: ASTM A572 is one of the high-strength, low-alloy steels (HSLA) and has properties similar to those of the SAE J410b steel specified by the SAE.

APPENDIX 8 DESIGN PROPERTIES OF CAST IRON

Material designation (ASTM number)	Grade	Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)	Modulus of elasticity (10^6 psi)	Modulus of elasticity (GPa)
Gray iron								
A48-94a	20	20	138			<1	12	83
	25	25	172			<1	13	90
	30	30	207			<1	15	103
	40	40	276			<1	17	117
	50	50	345			<1	19	131
	60	60	414			<1	20	138
Malleable iron								
A47-99	32510	50	345	32	221	10	25	172
	35018	53	365	35	241	18	25	172
A220-99	40010	60	414	40	276	10	26	179
	45006	65	448	45	310	6	26	179
	50005	70	483	50	345	5	26	179
	70003	85	586	70	483	3	26	179
	90001	105	724	90	621	1	26	179
Ductile iron								
A536-84	60-40-18	60	414	40	276	18	22	152
	80-55-06	80	552	55	379	6	22	152
	100-70-03	100	689	70	483	3	22	152
	120-90-02	120	827	90	621	2	22	152
Austempered ductile iron								
ASTM 897-90	1	125	850	80	550	10	22	152
	2	150	1050	100	700	7	22	152
	3	175	1200	125	850	4	22	152
	4	200	1400	155	1100	1	22	152
	5	230	1600	185	1300	<1	22	152

Notes: Strength values are typical. Casting variables and section size affect final values. Modulus of elasticity may also vary. Density of cast irons ranges from 0.25 to 0.27 lb/in^3 (6920 to 7480 kg/m^3). Compressive strength ranges 3 to 5 times higher than tensile strength.

APPENDIX 9 TYPICAL PROPERTIES OF ALUMINUM

Alloy and temper	Tensile strength		Yield strength		Ductility (percent elongation in 2 inches)	Shearing strength		Endurance strength	
	(ksi)	(MPa)	(ksi)	(MPa)		(ksi)	(MPa)	(ksi)	(MPa)
1060-O	10	69	4	28	43	7	48	3	21
1060-H14	14	97	11	76	12	9	62	5	34
1060-H18	19	131	18	124	6	11	121	6	41
1350-O	12	83	4	28	28	8	55		
1350-H14	16	110	14	97		10	69		
1350-H19	27	186	24	165		15	103	7	48
2014-O	27	186	14	97	18	18	124	13	90
2014-T4	62	427	42	290	20	38	262	20	138
2014-T6	70	483	60	414	13	42	290	18	124
2024-O	27	186	11	76	22	18	124	13	90
2024-T4	68	469	47	324	19	41	283	20	138
2024-T361	72	496	57	393	12	42	290	18	124
2219-O	25	172	11	76	18				
2219-T62	60	414	42	290	10			15	103
2219-T87	69	476	57	393	10			15	103
3003-O	16	110	6	41	40	11	121	7	48
3003-H14	22	152	21	145	16	14	97	9	62
3003-H18	29	200	27	186	10	16	110	10	69
5052-O	28	193	13	90	30	18	124	16	110
5052-H34	38	262	31	214	14	21	145	18	124
5052-H38	42	290	37	255	8	24	165	20	138
6061-O	18	124	8	55	30	12	83	9	62
6061-T4	35	241	21	145	25	24	165	14	97
6061-T6	45	310	40	276	17	30	207	14	97
6063-O	13	90	7	48		10	69	8	55
6063-T4	25	172	13	90	22				
6063-T6	35	241	31	214	12	22	152	10	69
7001-O	37	255	22	152	14				
7001-T6	98	676	91	627	9			22	152
7075-O	33	228	15	103	16	22	152		
7075-T6	83	572	73	503	11	48	331	23	159

Note: Common properties:
Density: 0.095 to 0.102 lb/in^3 (2635 to 2829 kg/m^3)
Modulus of elasticity: 10 to 10.6 $\times$ 10^6 psi (69 to 73 GPa)
Endurance strength at 5 $\times$ 10^8 cycles

Problems:

Solve problems No. 20, 21, 22, 23, 25, and 26.