Material Selection and Heat Treatment Part II Metalurgical Characteristics

National Broach & Machine Division of Lear Siegler
Mt. Clemens, MI 48044

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Metallurgical Characteristics*

The approximate tensile strength of any steel is measured by its hardness, Table 1. Since hardness is determined by both chemical composition and heat treatment, these are the two important metallurgical considerations in selecting gear steels.

Chemical Composition

Hardenable gear steels are of two types: through-hardenable or case-hardenable. Through-hardenable steels contain alloying elements and usually have carbon content ranging from about 0.40 to 0.50-percent to give the desired hardness. Steels for case-hardening may or may not contain alloying elements, but have lower carbon content (usually less than 0.25-percent). The lower carbon content permits development of high surface hardness while retaining a softer, more ductile core.

An alloy steel, Table 2, is a type to which one or more alloying elements have been added to give it properties that cannot be obtained in carbon steel. Chromium is one of the most versatile and widely used alloying elements. It produces corrosion and oxidation resistance, and induces high hardness and wear resistance. It also intensifies the action of carbon, increases the elastic limit, increases tensile strength, and increases depth of hardness penetration.

Nickel increases shock resistance, elastic limit, and tensile strength of steel. Nickel steels are particularly suitable for case-hardening. This results in their frequent use for aircraft gears where strength-to-weight ratio must be high. The strong, tough case obtained with nickel steels combined with good core properties provides exceptional fatigue and wear resistance. Simplified hardening procedures and low distortion during heat treatment result from lower transformation temperature ranges and the relatively small difference between case and core transformation temperatures.

Molybdenum increases hardenability of steels and has a significant effect on softening of steels at tempering temperatures. It markedly retards softening of the hardened martensite at tempering temperatures above 450F.

Vanadium is used as an alloying element in steels for two reasons. First is the effect on grain size at elevated temperatures. Vanadium stabilizes the fine grain structure of austenitized steels and permits retention of excellent ductility and impact resistance while developing high tensile and yield strengths. The second reason is the ability to form carbides which remain stable at elevated temperatures.

Hardenability is the property of a steel which determines the depth and distribution of the hardness induced by quenching. The higher the hardenability of a steel, the greater the depth to which the steel can be hardened and the slower the quench which can be used. Hardenability should not be confused with hardness or maximum hardness which can be obtained by heat treatment, since that depends almost entirely

**Implemented and reviewed by Harold A. Maloney, plant metallurgist, Clark Equipment Co.*

Table 1 – Approximate Tensile Strength for Equivalent Hardness Numbers of Steel

Brinell Indentation Diameter, mm	Brinell Hardness Number, 3000-Kg 10 mm Tungsten Carbide Ball	Rockwell Hardness Number: B-Scale 100-Kg Load 1/16 in. Ball	Rockwell Hardness Number: C-Scale 150-Kg Load Brale Penetrator	Vickers Diamond Pyramid Hardness Number	Shore Scleroscope Hardness Number	Approx. Tensile Strength 1000 p.s.i.
2.25	745	—	65.3	840	91	—
—	710	—	63.3	780	87	—
2.35	682	—	61.7	737	84	—
2.40	653	—	60.0	697	81	—
2.45	627	—	58.7	667	79	—
2.50	601	—	57.3	640	77	—
2.55	578	—	56.0	615	75	—
2.60	555	—	54.7	591	73	298
2.65	534	—	53.5	569	71	288
2.70	514	—	52.1	547	70	274
2.75	495	—	51.0	528	68	264
2.80	477	—	49.6	508	66	252
2.85	461	—	48.5	491	65	242
2.90	444	—	47.1	472	63	230
2.95	429	—	45.7	455	61	219
3.00	415	—	44.5	440	59	212
3.05	401	—	43.1	425	58	202
3.10	388	—	41.8	410	56	193
3.15	375	—	40.4	396	54	184
3.20	363	—	39.1	383	52	177
3.25	352	(110.0)	37.9	372	51	170
3.30	341	(109.0)	36.6	360	50	163
3.35	331	(108.5)	35.5	350	48	158
3.40	321	(108.0)	34.3	339	47	152
3.45	311	(107.5)	33.1	328	46	147
3.50	302	(107.0)	32.1	319	45	143
3.55	293	(106.0)	30.9	309	43	139
3.60	285	(105.5)	29.9	301	—	136
3.65	277	(104.5)	28.8	292	41	131
3.70	269	(104.0)	27.6	284	40	128
3.75	262	(103.0)	26.6	276	39	125
3.80	255	(102.0)	25.4	269	38	121
3.85	248	(101.0)	24.2	261	37	118
3.90	241	100.0	22.8	253	36	114
3.95	235	99.0	21.7	247	35	111
4.00	229	98.2	20.5	241	34	109
4.05	223	97.3	(18.8)	234	—	104
4.10	217	96.4	(17.5)	228	33	103
4.15	212	95.5	(16.0)	222	—	100
4.20	207	94.6	(15.2)	218	32	99
4.25	201	93.8	(13.8)	212	31	97
4.30	197	92.8	(12.7)	207	30	94
4.35	192	91.9	(11.5)	202	29	92
4.40	187	90.7	(10.0)	196	—	90
4.45	183	90.0	(9.0)	192	28	89
4.50	179	89.0	(8.0)	188	27	88
4.55	174	87.8	(6.4)	182	—	86
4.60	170	86.8	(5.4)	178	26	84
4.65	167	86.0	(4.4)	175	—	83
4.70	163	85.0	(3.3)	171	25	82
4.80	156	82.9	(0.9)	163	—	80
4.90	149	80.8	—	156	23	—
5.00	143	78.7	—	150	22	—
5.10	137	76.4	—	143	21	—
5.20	131	74.0	—	137	—	—
5.30	126	72.0	—	132	20	—
5.40	121	69.8	—	127	19	—
5.50	116	67.6	—	122	18	—
5.60	111	65.7	—	117	15	—

The indentation and hardness values in the foregoing table are taken from Table 2, Approximate Equivalent Hardness Numbers for Brinell Hardness Numbers for Steel, pages 122 and 123 of 1952 SAE Handbook, Society of Automotive Engineers, Incorporated.

The values shown in parentheses are beyond the normal range of the test scale and are given only for comparison with other values.

Courtesy Republic Steel Corp.

Table 2 – Basic AISI and SAE Numbering System for Steels

Numerals and Digits	Type of Steel and Average Chemical Contents, %
	CARBON STEELS
10XX	Plain Carbon (Mn 1.00% max)
11XX	Resulphurized
12XX	Resulphurized and Rephosphorized
15XX	Plain Carbon (max Mn range—over 1.00—1.65%)
	MANGANESE STEELS
13XX	Mn 1.75
	NICKEL STEELS
23XX	Ni 3.50
25XX	Ni 5.00
	NICKEL-CHROMIUM STEELS
31XX	Ni 1.25; Cr 0.65 and 0.80
32XX	Ni 1.75; Cr 1.07
33XX	Ni 3.50; Cr 1.50 and 1.57
34XX	Ni 3.00; Cr 0.77
	MOLYBDENUM STEELS
40XX	Mo 0.20 and 0.25
44XX	Mo 0.40 and 0.52
	CHROMIUM-MOLYBDENUM STEELS
41XX	Cr 0.50, 0.80 and 0.95; Mo 0.12, 0.20, 0.25 and 0.30
	NICKEL-CHROMIUM-MOLYBDENUM STEELS
43XX	Ni 1.82; Cr 0.50 and 0.80; Mo 0.25
43BVXX	Ni 1.82; Cr 0.50; Mo 0.12 and 0.25; V 0.03 minimum
47XX	Ni 1.05; Cr 0.45; Mo 0.20 and 0.35
81XX	Ni 0.30; Cr 0.40; Mo 0.12
86XX	Ni 0.55; Cr 0.50; Mo 0.20
87XX	Ni 0.55; Cr 0.50; Mo 0.25
88XX	Ni 0.55; Cr 0.50; Mo 0.35
93XX	Ni 3.25; Cr 1.20; Mo 0.12
94XX	Ni 0.45; Cr 0.40; Mo 0.12
97XX	Ni 0.55; Cr 0.20; Mo 0.20
98XX	Ni 1.00; Cr 0.80; Mo 0.25
	NICKEL-MOLYBDENUM STEELS
46XX	Ni 0.85 and 1.82; Mo 0.20 and 0.25
48XX	Ni 3.50; Mo 0.25
	CHROMIUM STEELS
50XX	Cr 0.27, 0.40, 0.50 and 0.65
51XX	Cr 0.80, 0.87, 0.92, 0.95, 1.00 and 1.05
501XX	Cr 0.50
511XX	Cr 1.02
521XX	Cr 1.45
	CHROMIUM VANADIUM STEELS
61XX	Cr 0.60, 0.80 and 0.95; V 0.10 and 0.15 minimum
	TUNGSTEN CHROMIUM STEELS
71XXX	W 13.50 and 16.50; Cr 3.50
72XX	W 1.75; Cr 0.75
	SILICON MANGANESE STEELS
92XX	Si 1.40 and 2.00; Mn 0.65, 0.82 and 0.85; Cr 0.00 and 0.65
	LOW ALLOY HIGH TENSILE STEELS
9XX	Various
	STAINLESS STEELS
	(Chromium-Manganese-Nickel)
302XX	Cr 17.00 and 18.00; Mn 6.50 and 8.75, Ni 4.50 and 5.00
	(Chromium-Nickel)
303XX	Cr 8.50, 15.50, 17.00, 18.00, 19.00, 20.00, 20.50, 23.00, 25.00 Ni 7.00, 9.00, 10.00, 10.50, 11.00, 11.50, 12.00, 13.00, 13.50, 20.50, 21.00, 35.00
	(Chromium)
514XX	Cr 11.12, 12.25, 12.50, 13.00, 16.00, 17.00, 20.50 and 25.00
515XX	Cr 5.00
	BORON INTENSIFIED STEELS
XXBXX	B denotes Boron Steel
	LEADED STEELS
XXLXX	L denotes Leaded Steel

NOTE: "XX" after numbers or letters in table indicates carbon percentage; i.e. 1040 indicates 0.40 percent carbon.

From SAE Iron and Steel Handbook Supplement 30

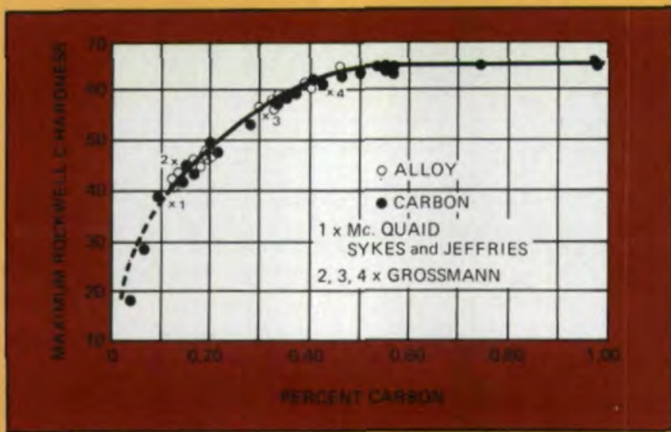

Fig. 1 – Relationship of maximum quenched hardness of alloy and carbon steels to carbon content. *Courtesy Republic Steel Corp.*

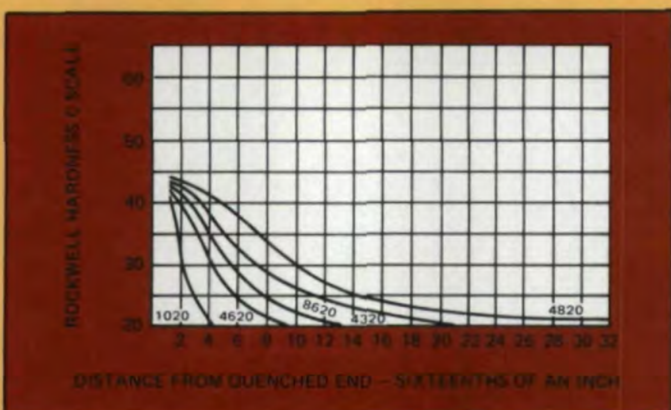

Fig. 2 – Comparative hardenability of 0.20-percent carbon alloy steels. *Courtesy Republic Steel Corp.*

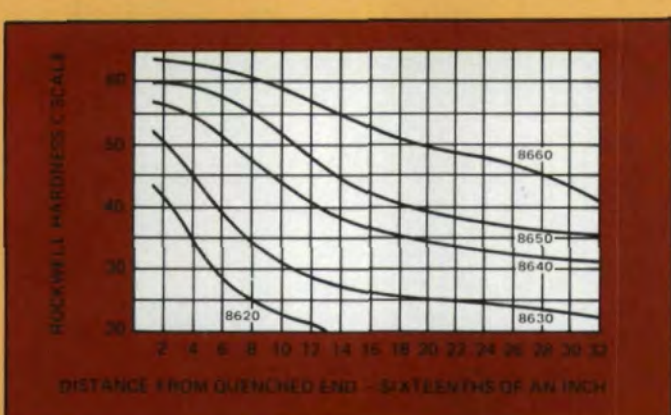

Fig. 3 – Comparative hardenability of 8600 Alloy Steels. *Courtesy Republic Steel Corp.*

on carbon content, Fig. 1. Also, section thickness has considerable influence on the maximum hardness obtained for a given set of conditions; the thicker the section, the slower the quench rate will be. Variations in test bar hardenability curves for various 0.20-percent carbon and alloy steels is shown in Fig. 2. Similar hardenability curves for 8600 alloy steels with various carbon contents is shown in Fig. 3. Maximum hardenability of case-hardened 8620 steel is achieved, Fig. 4, when the case carbon concentration is 0.80-percent.

H-steels are guaranteed by the supplier to meet established hardenability limits for specific grades of steel. These steels

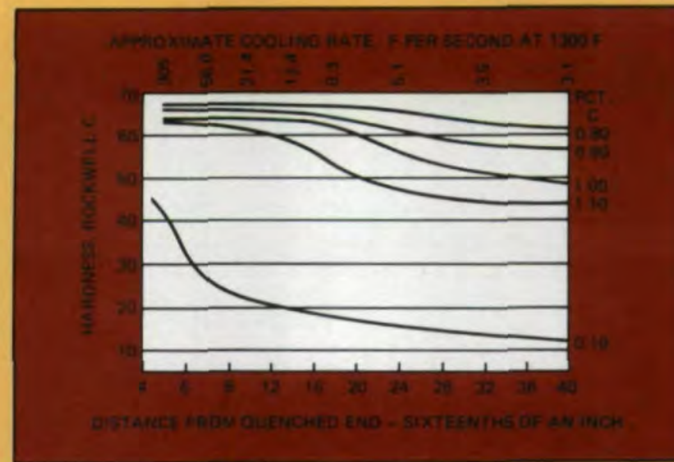

Fig. 4 – Curves showing that maximum hardenability of 8620 steel is achieved when case carbon concentration is at 0.80-percent carbon. *Courtesy Climax Molybdenum Co.*

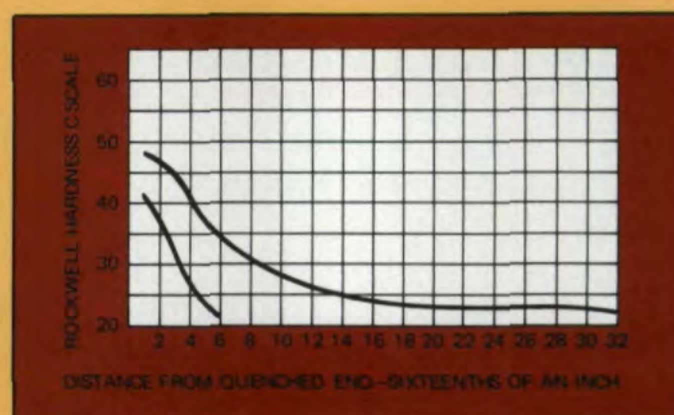

Fig. 5 – Hardenability upper and lower curve limits for 8620H steel. *SAE Iron and Steel Handbook Supplement 30.*

are designated by an "H" following the composition code number, such as 8620H, Fig. 5. Hardenability of H-steels and a steel with the same chemical composition is not necessarily the same. Therefore, H-steels are often specified when it is essential that a given hardness be obtained at a given point below the surface of a gear tooth.

E-5 ON READER REPLY CARD

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CALCULATION OF SPUR GEAR TOOTH . . .

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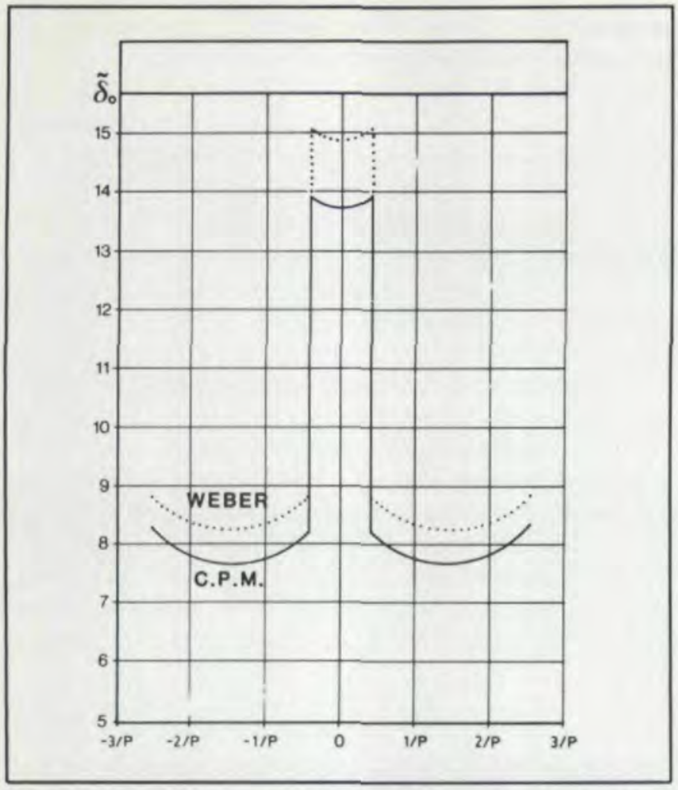

Fig. 9 – Combined flexibility curve $\tilde{\delta}_0$ versus abscissa of load on line of action for a pair of identical standard AGMA gears (40 teeth, 20 deg); W = 1 000 lb/in., P = 0.5, comparison with Weber's curve.

of the contact zone as calculated from Hertz's theory. Contact width may be calculated at each point on the line of action and depends in a nonlinear fashion on absolute dimensions, material properties and transmitted load. This being known, the flexibility curve for the given pair of gears may be obtained, including the load sharing effect. Comparison with published results by Weber,[3] Chabert,[7] and Cornell[10] shows good agreement regarding the shape of flexibility curves, except for a slight shift between these curves, which is due, probably, to the selection of different reference points.

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