STEEL CASTINGS HANDBOOK

SUPPLEMENT 5

GENERAL PROPERTIES OF STEEL CASTINGS

STEEL FOUNDERS'
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Steel Castings Handbook
Supplement 5

General Properties of Steel Castings

Preface

Steel castings, whenever possible, are purchased to property requirements rather than to chemical analysis specifications. Thus, the foundry engineer can select the alloy compositions which best satisfy mechanical property specifications. Most of the national specifications are written in the terms of the alloy type plus tensile properties and in some cases, hardness values, impact values, and hardenability ranges.

The property values presented in this supplement are those which may be expected from carbon and low alloy cast steels in general. Mechanical properties have been determined from test specimens prepared in accordance with standard practice.

Additional information on carbon and low alloy steels, as well as wear-resistant steels, corrosion-resistant alloys, both high alloy and nickel base, heat-resistant alloys and low temperature and cryogenic steels is fully discussed in the Steel Castings Handbook, 5th Edition, published by the Steel Founders' Society of America.

Contents

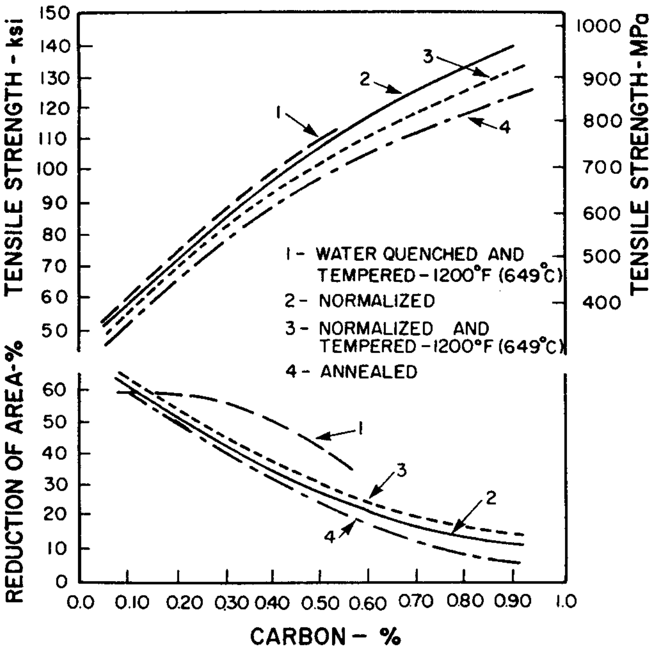

Fig. 1 Tensile strength and reduction of area vs. carbon content of cast carbon steels (1).

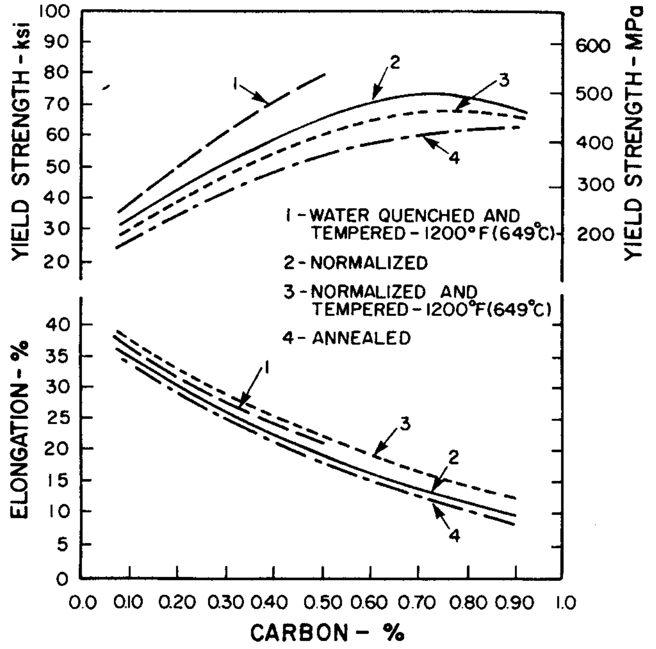

Fig. 2 Yield strength and elongation vs. carbon content of cast carbon steels (1).

DEFINITIONS AND ALLOY CLASSIFICATIONS

Carbon steels contain only carbon as the principal alloying element. Other elements are present in small quantities including those added for deoxidation. Silicon and manganese in cast carbon steels typically range from 0.25 to about 0.80% Si, and 0.50 to about 1.00% Mn, respectively. Carbon steels are classified by their carbon content into:

Low carbon steel . . . . . $C \leq 0.20\%$
Medium carbon steel . . . . $C = 0.20\text{–}0.50\%$
High carbon steel . . . . . $C \geq 0.50\%$

Low alloy steels contain alloying elements, in addition to carbon, up to a total alloy content of 8%. Cast steel containing more than the following amounts of a single alloying element is considered low alloy cast steel:

Manganese	1.00%
Silicon	0.80
Nickel	0.50
Copper	0.50
Chromium	0.25
Molybdenum	0.10
Vanadium	0.05
Tungsten	0.05

For deoxidation of carbon and low alloy steels, i.e. for control of their oxygen content, the elements aluminum, titanium, and zirconium are used. Of these elements, aluminum is used most frequently, because of its effectiveness and low cost.

Numerous types of cast low alloy steel grades exist to meet the specific requirements of the end use, such as structural strength and resistance to wear, heat, and corrosion. The designations of the American Iron and Steel Institute, AISI, and the Society of Automotive Engineers, Inc., SAE, have historically been used to identify the various types of steel by their principal alloy content (Appendix A)*. Cast steels, however, do not follow precisely the composition ranges specified by AISI and SAE designations for wrought steels. In most cases the cast steel grades will contain 0.30 to 0.65% Si, and 0.50 to 1.00% Mn, unless specified differently. The principal low alloy cast steel designations, their AISI and SAE equivalents, and their alloy type are listed below:

Cast Steel Designation	Nearest Equivalent AISI and SAE Designation	Alloy Type
1300	1300	Mn
8000,8400	8000,8400	Mn-Mo
80B00	80B00	Mn-Mo-B
2300	2300	Ni
8600,4300	8600,4300	Ni-Cr-Mo
9500	9500	Mn-Ni-Cr-Mo
4100	4100	Cr-Mo

The AISI no longer uses the 8000, 8400, 2300, and 9500 designations. However, because these alloy types are used extensively as cast steels, their cast steel designation numbers are continued in the steel casting industry. There are additional alloy types which are infrequently specified as cast steels, namely: 3100 (Ni-Cr), 3300 (Ni-Cr), 4000 (Mo), 5100 (Cr), 6100 (Cr-V), 4600 (Ni-Mo), and 9200 (Si).

AMBIENT TEMPERATURE PROPERTIES

Property Ranges and Trends

Carbon and low alloy steel castings are produced to a great variety of properties because composition

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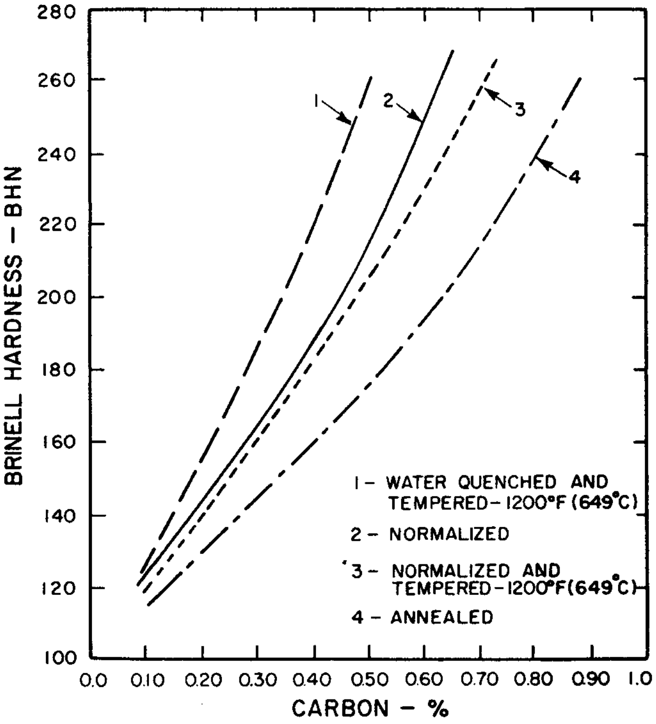

Fig. 3 Hardness vs. carbon content of cast carbon steels (**1**).

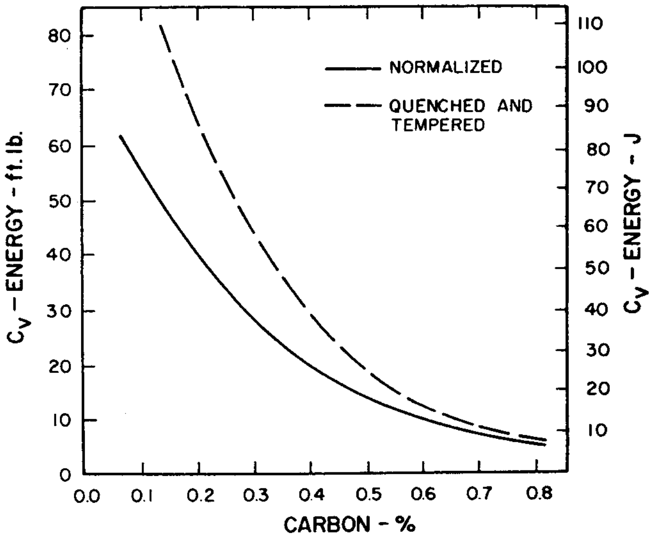

Fig. 4 Room temperature Charpy V-notch values vs. carbon content of cast carbon steel in the normalized and tempered condition [tempering temperature 1200°F (650°C)] (**1**).

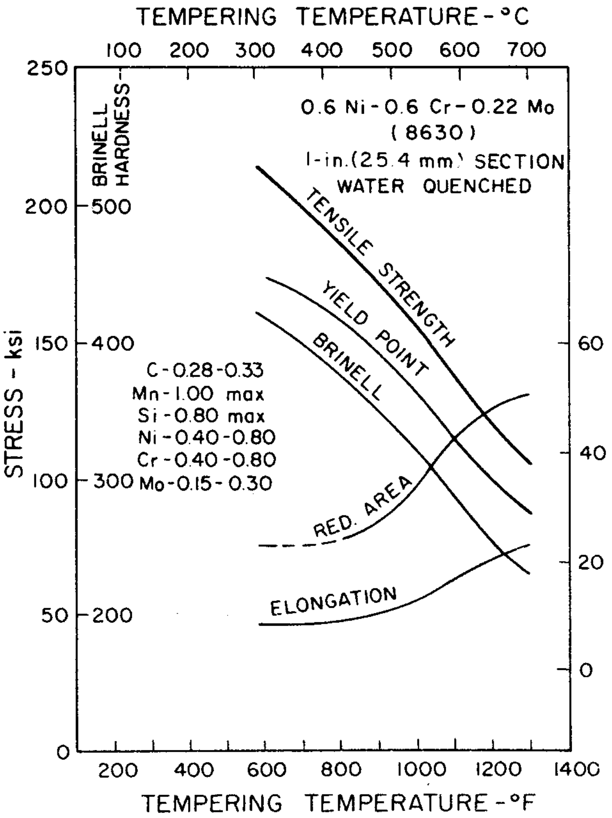

Fig. 5 Mechanical properties of 0.6Ni-0.6Cr-0.22Mo cast 8630 steel (**2**).

and heat treatment can be selected to achieve specific combinations of properties, including hardness, strength, ductility, fatigue, and toughness. While selections can be made from a wide range of properties, it is important to recognize the interrelationship of these properties. For example, higher hardness, lower toughness, and lower ductility values are associated with higher strength values.

Property trends among carbon steels are illustrated as a function of the carbon content in Figures 1 through 4. Unless otherwise noted, the properties discussed refer to those obtained from specimens which have been removed from standard ASTM keel blocks, which are made with a 1.25-in. (32-mm) section size. The subject of how these properties are affected by larger section sizes is discussed in this supplement under the heading Section Size, Mass Effects.

For low alloy steels, the properties of Ni-Cr-Mo cast 8630 grade in Figure 5 illustrate the range of properties which can be achieved with a single material and the interrelationship of its mechanical properties. These relationships and mechanical property ranges will be further discussed in the following paragraphs for carbon and low alloy cast steels.

Strength-Hardness. Depending on alloy choice and heat treatment, ultimate tensile strength levels from 60 to 250 ksi (414–1724 MPa) can be achieved with cast carbon and low alloy steels.

For cast carbon steels Figure 6 illustrates tensile strength and tensile ductility values which can be expected from normalized steels and from quenched and tempered steels having Brinell hardness values within the range of 120 to 280 BHN.

For carbon steel the hardness and strength values are largely determined by the carbon content and the heat treatment as illustrated in Figure 3. The effect

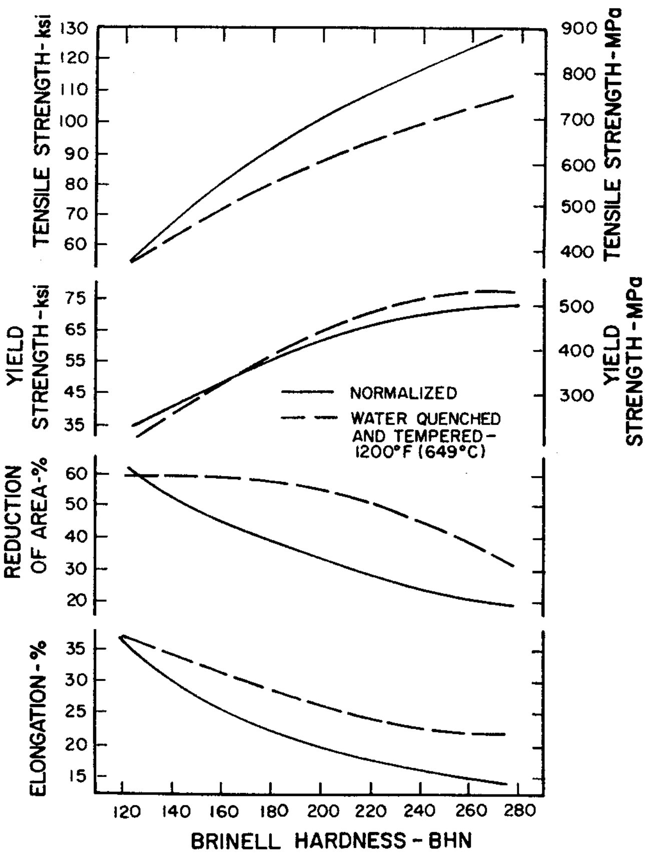

Fig. 6 Tensile properties of cast carbon steels as a function of hardness (**1**).

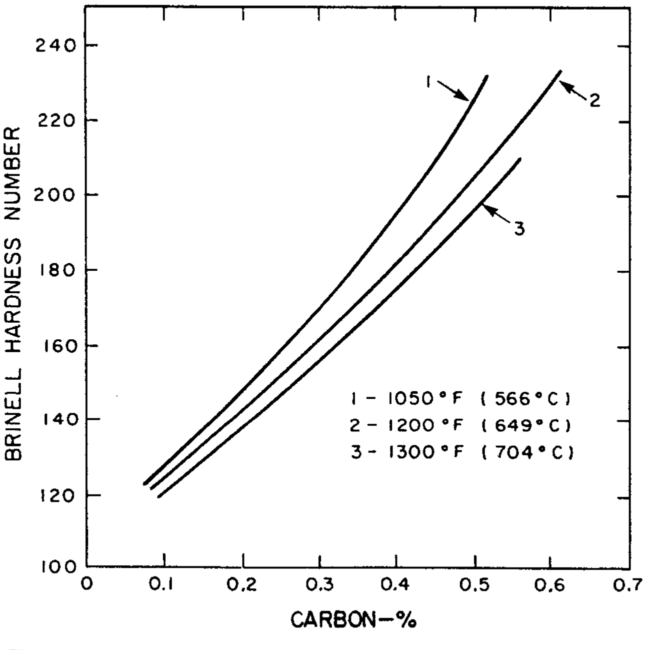

Fig. 7 Hardness vs. carbon content of normalized cast carbon steels tempered at various temperatures for two hours (**1**).

of tempering normalized carbon steel is shown by data in Figure 7.

The normally expected Brinell hardness-ultimate tensile strength combinations of cast low alloy steels are shown in Figure 8. The proportionality of strength to hardness is widely recognized.

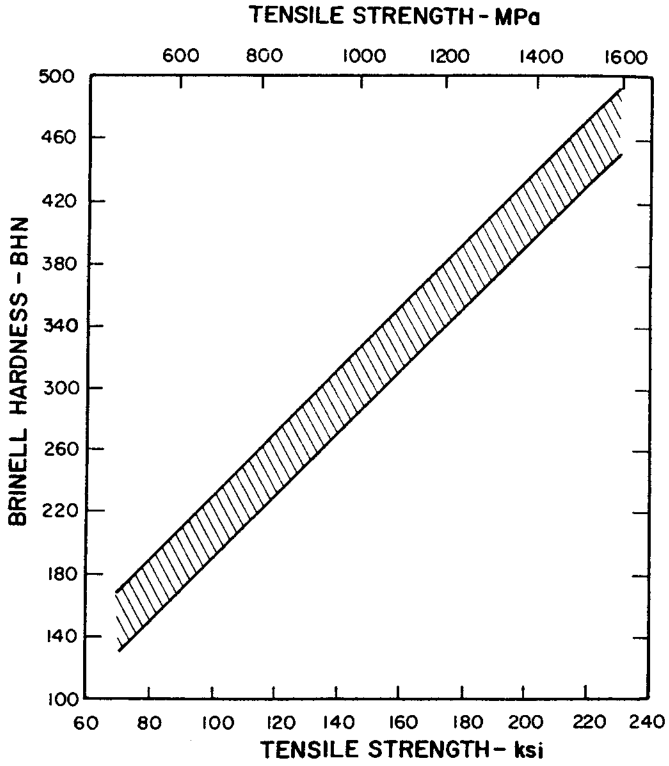

Fig. 8 Hardness vs. tensile strength of low alloy cast steels regardless of heat treatment (**1**).

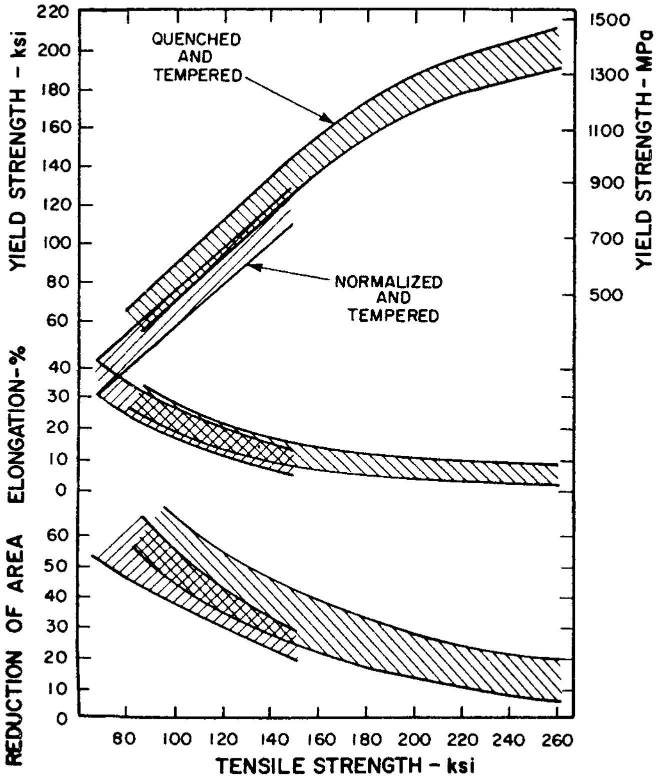

Fig. 9 Tensile properties of cast low alloy steels in the quenched and tempered and in the normalized and tempered conditions (**1**).

Strength-Ductility. Ductility depends on the

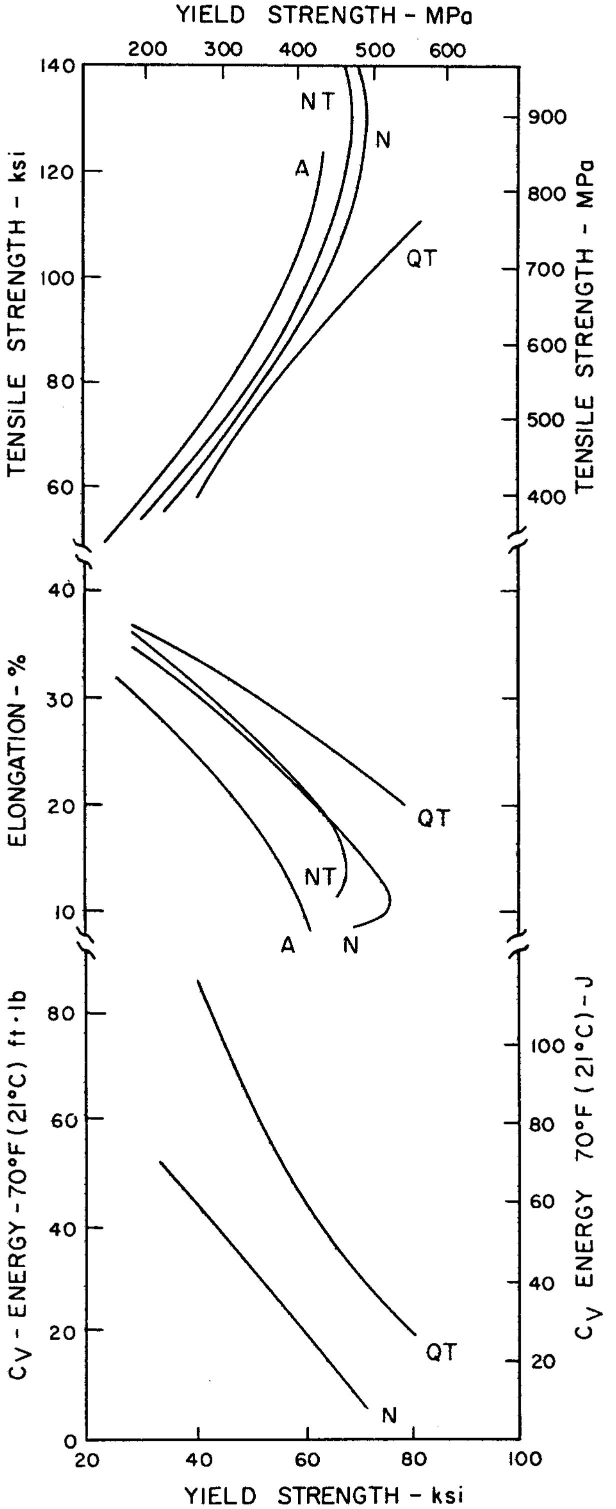

Fig. 10 Room temperature properties of cast carbon steels. QT = quenched, tempered at 1200°F (650°C). N = normalized. NT = normalized, tempered at 1200°F (650°C). A = annealed (3).

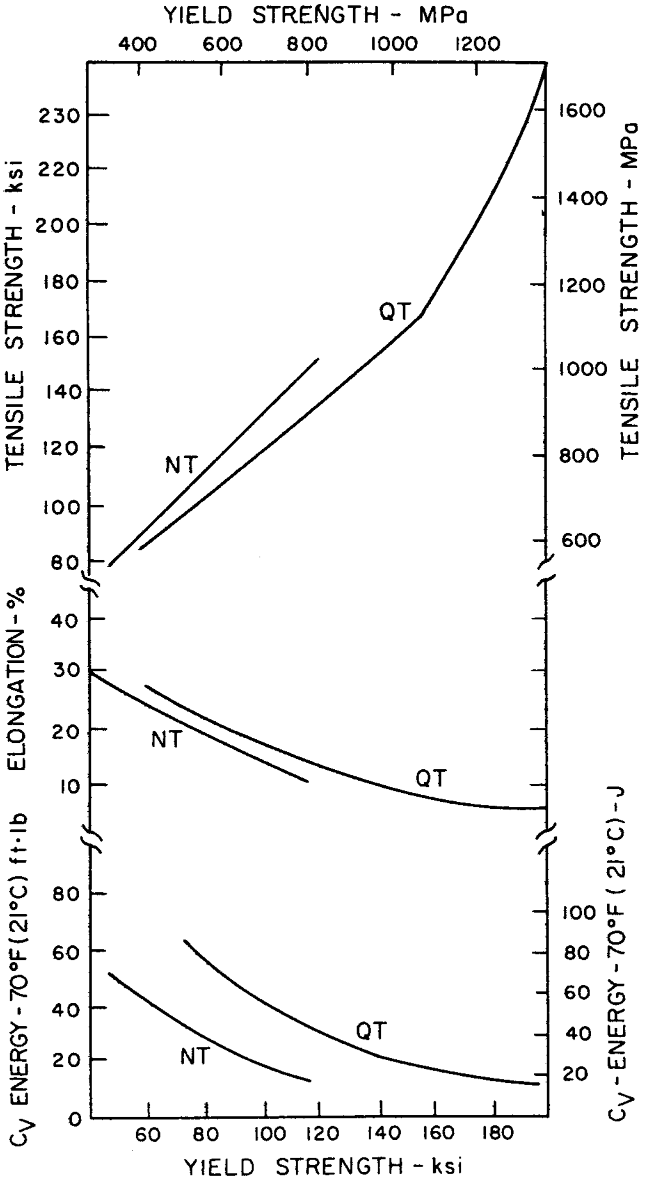

Fig. 11 Room temperature properties of cast low-alloy steels. QT = quenched and tempered. NT = normalized and tempered (3).

strength, or hardness, of the cast steel to a very large extent (Figures 6 and 9). Actual ductility requirements vary, of course, with the strength level and the specification to which a steel is ordered (Chapter 27—Specifying Steel Castings*). Because yield strength is a primary design criterion for structural applications, the relationships of Figures 1, 2, and 9 are replotted in Figures 10 and 11 to reveal the major trends for cast carbon and low alloy steels. Quenched and tempered steels exhibit the higher ductility values for a given yield strength level compared to normalized, normalized and tempered, and annealed steels.

Strength-Toughness. Several test methods exist to evaluate toughness of steel, or the resistance to sudden or brittle fracture. These include the Charpy V-notch impact test, the dropweight test, the dynamic tear test and specialized procedures to determine plane strain fracture toughness. Results of all these tests are in use and will be reviewed here because each of these tests offers specific advantages that are unique to the test method as discussed in Chapter 4—Functional Considerations in Design.*

Charpy V-notch impact energy trends at room tem-

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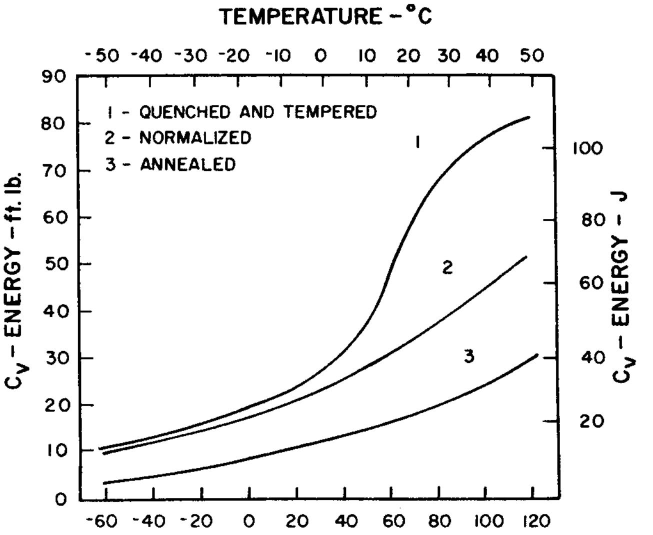


Fig. 12 Effect of various heat treatments on the Charpy V-notch transition curves of a 0.30% carbon steel (**1**).

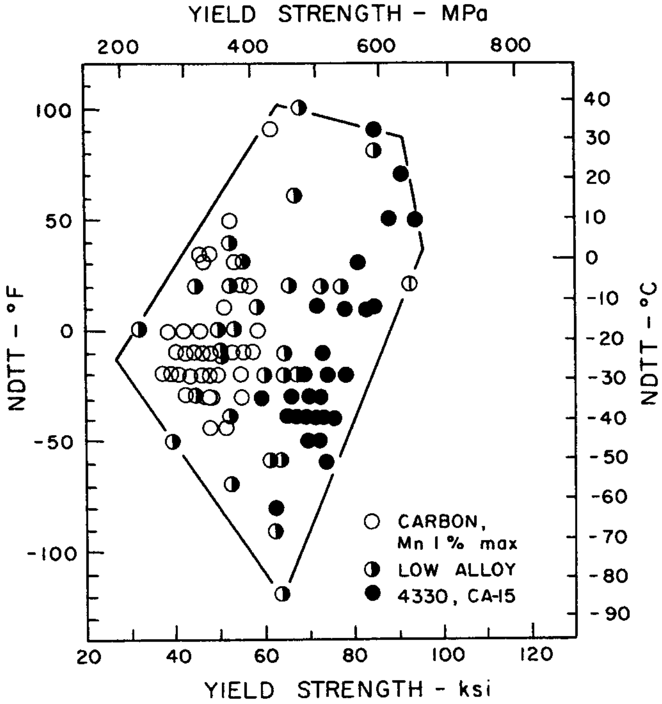


Fig. 14 The NDTT and yield strength of normalized and tempered commercial cast steels [1.5-in. (38-mm) section] (**5**).

perature in Figures 10 and 11 reveal the distinct effect of strength and heat treatment on toughness. Higher toughness is obtained when a steel is quenched and tempered, rather than normalized and tempered. The effect of heat treatment and testing temperature on Charpy V-notch toughness is further illustrated in Figures 12 and 13 for a carbon steel and for a low alloy cast 8630 steel. Quenching, followed by tempering, produces superior toughness as indicated by the shift of the impact energy transition curve to lower temperatures. The improved toughness of quenched and tempered steels is realized in spite of the higher strength level as evident for the cast 8630 low alloy steel (Fig. 13).

Nil ductility transition temperatures, NDTT, from +100°F (38°C) to as low as −130°F (−90°C) have been recorded in tests on normalized and tempered cast

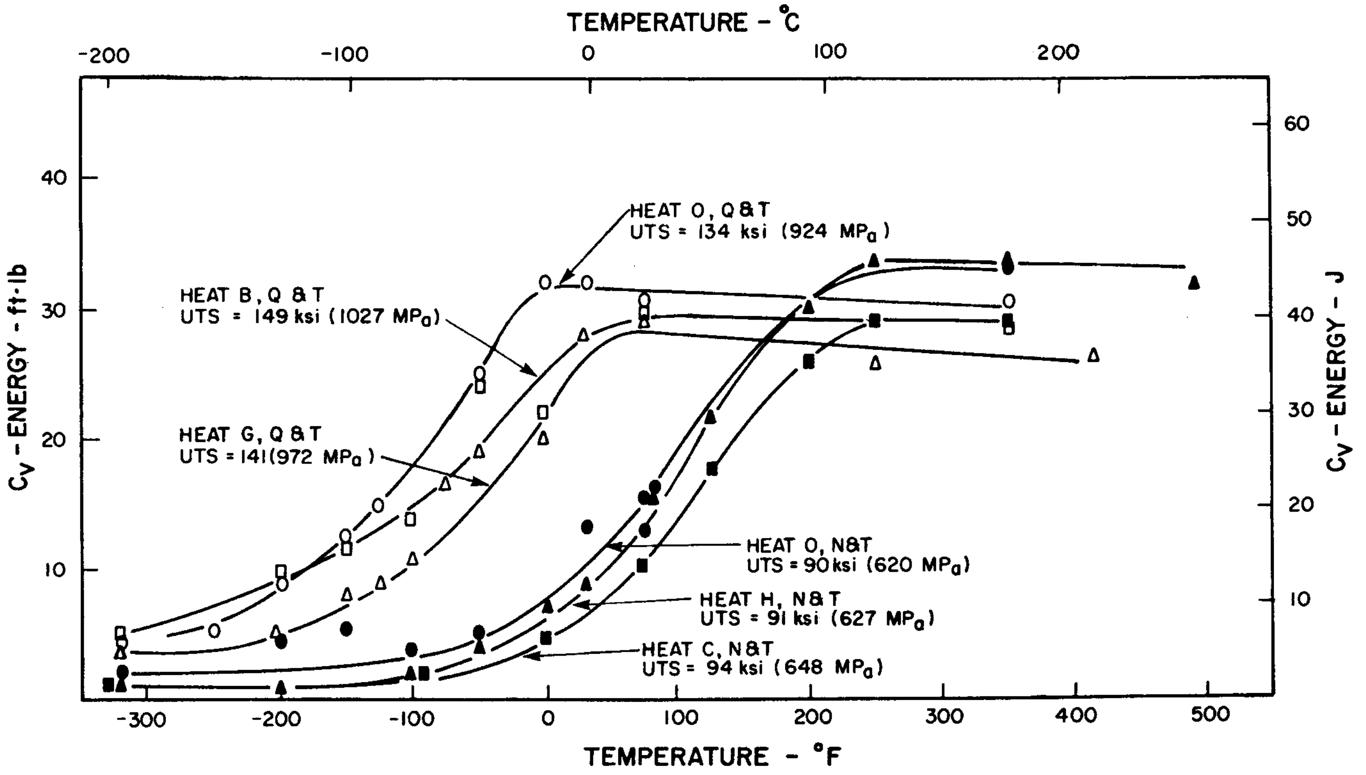


Fig. 13 Charpy V-notch test results for various heats of cast 8630 steel in the quenched and tempered and normalized and tempered condition (4).

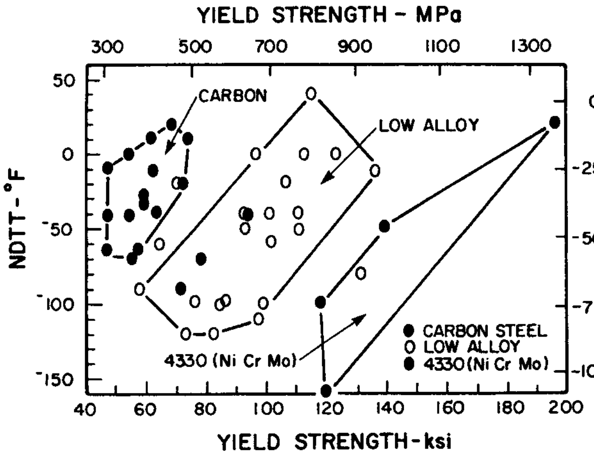


Fig. 15 The NDTT and yield strength of quenched and tempered commercial cast steels [1.5-in. (38-mm) section] (5).

carbon and low alloy steels in the yield strength range of 30 to 95 ksi (207 to 655 MPa) (Figure 14). Comparison of the data in Figure 14 with those of Figure 15 shows the superior toughness values, at equal strength levels, which low alloy steels offer compared to carbon steels. When cast steels are quenched and tempered, the range of strength and of toughness is thus broadened (Figure 15). NDTT values of as high as +50°F (+10°C) to as low as −160°F (−107°C) can be obtained in the yield strength range of 50 to 195 ksi (345 to 1345 MPa) depending on alloy selection (Figure 15).

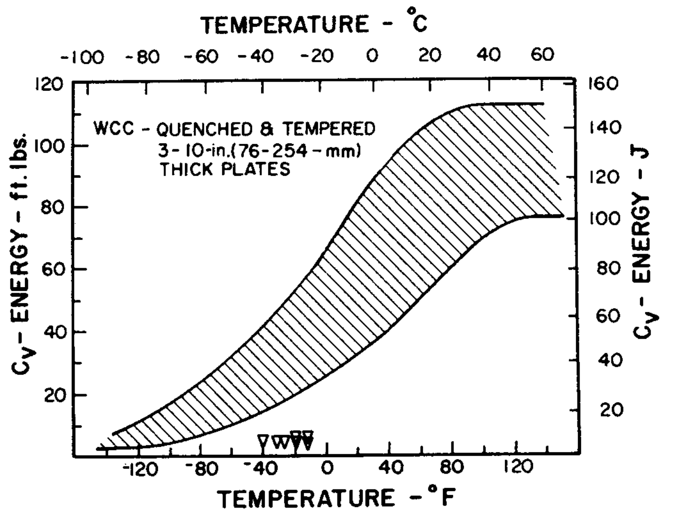
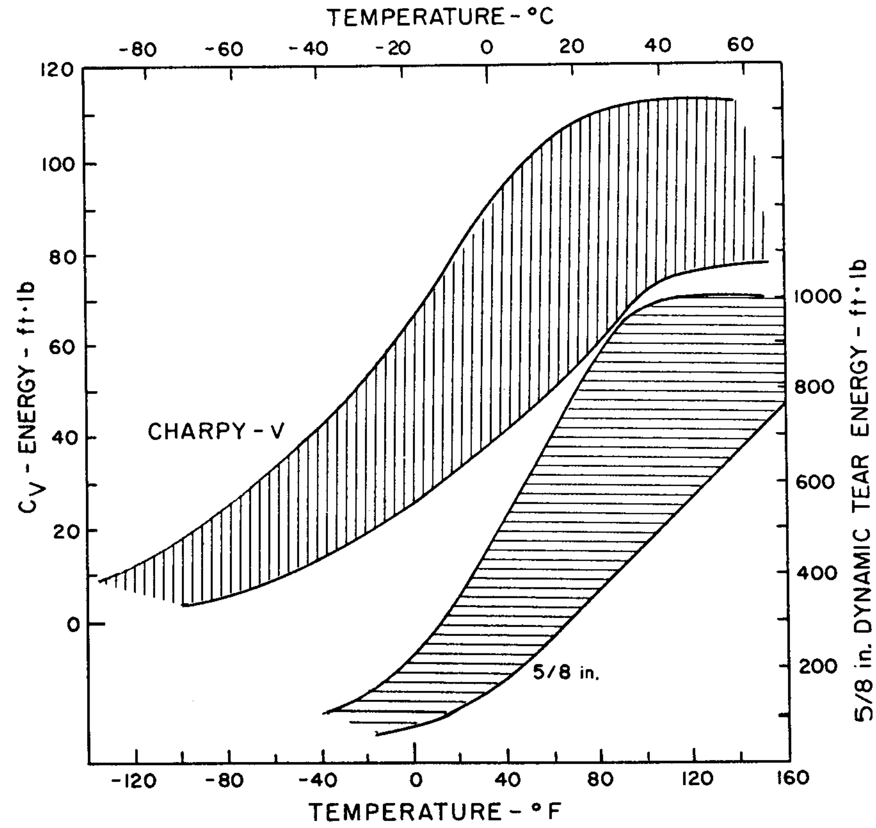


Fig. 16 NDTT values (triangles) and the scatter band of Charpy V-notch energy transition curves of several quenched and tempered C-Mn cast steels (A216, grade WCC). Nominal ultimate tensile strength = 80 ksi (552 MPa) (1).

An approximate relationship exists between the Charpy V-notch impact energy-temperature behavior and the NDTT. The NDTT frequently coincides with the energy transition temperature determined in Charpy V-notch tests. Applicable data for cast C-Mn steels of the A216, WCC type are shown in Figure 16.

Dynamic tear impact energy results relate to strength, heat treatment, and alloy content in a manner similar to those of Charpy V-notch impact and drop-

Fig. 17 Scatter bands of Charpy V-notch and dynamic tear energy transition curves from several heats of C-Mn steel of ASTM A216, type WCC. Values represent surface and center locations of 3-in. (76-mm) plate castings (1). Conversion: 1 ft·lb = 1.356 J.



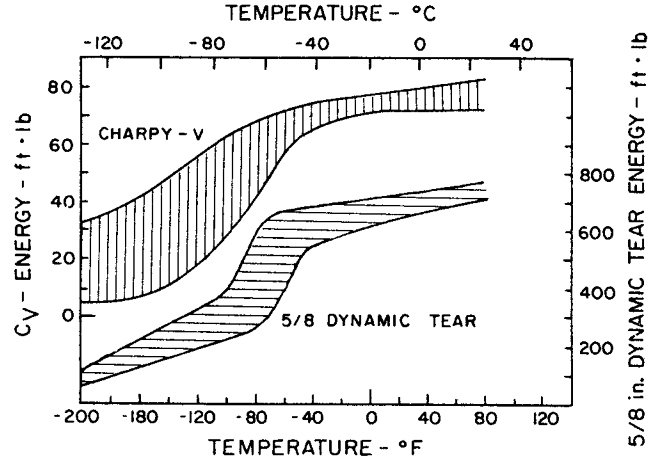


Fig. 18 Scatter bands of Charpy V-notch and dynamic tear energy transition curves from several heats of Ni-Cr-Mo steel, HY-80 type. Values represent surface and center location of 3-in. (76-mm) plate castings (1). Conversion: 1 ft·lb = 1.356 J.

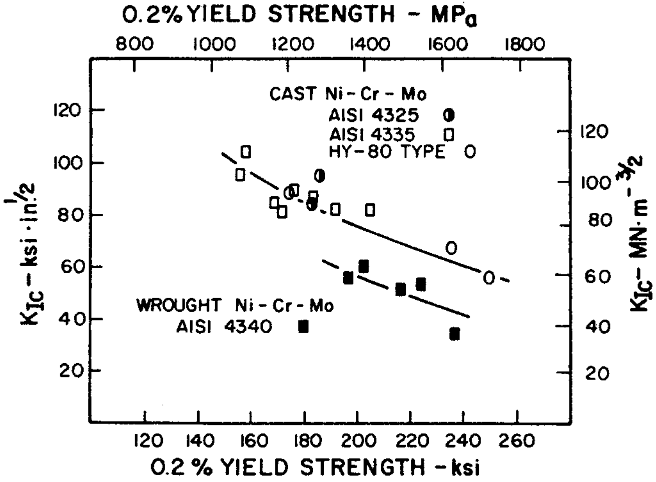


Fig. 19 Plane strain fracture toughness, K_{Ic}, to strength relationships at room temperature for quenched and tempered Ni-Cr-Mo steels (8-14).

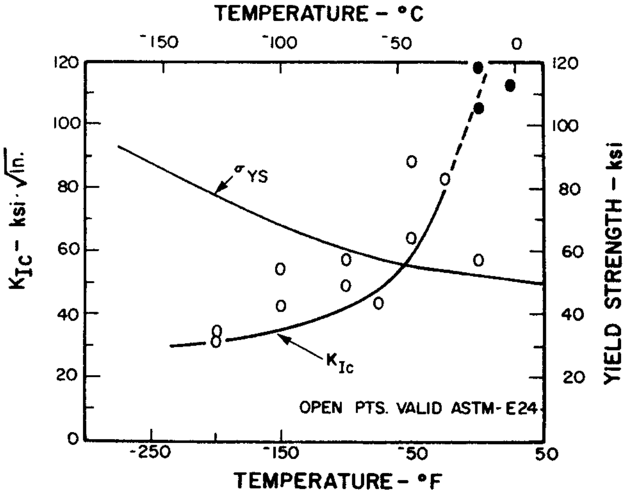


Fig. 20 Temperature dependence of yield strength and K_{Ic} fracture toughness for an A216 (WCC Grade) large steel casting, 20 × 20 × 48 in. (508 × 508 × 1219 mm) keel block (6). Conversion: 1 ksi·in.$^{1/2}$ = 1.1 MN·m$^{-3/2}$, and 1 ksi = 6.89 MPa.

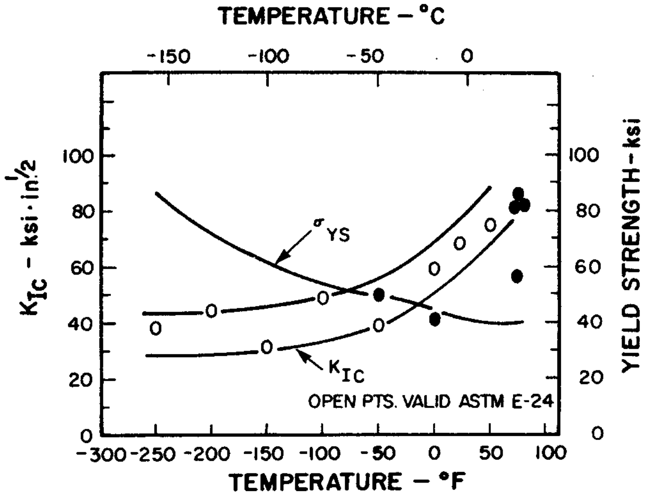


Fig. 21 Temperature dependence of yield strength and K_{Ic} fracture toughness for 1.25Cr-.5MO-.2V large steel casting. (6). Conversion: 1 ksi·in.$^{1/2}$ = 1.1 MN·m$^{-3/2}$, and 1 ksi = 6.89 MPa.

weight tests. Data for C-Mn and Ni-Cr-Mo steels are shown in Figure 17 and 18, along with Charpy V-notch impact test results.

Plane strain fracture toughness, K_{Ic}, data for a variety of steels in Table 1 reflect the important strength-toughness relationship. For quenched and tempered Ni-Cr-Mo steels, Figure 19 indicates high K_{Ic} values of about 100 ksi·in.$^{1/2}$ (110 MN·m$^{-3/2}$) at a 0.2% offset yield strength level of 150 ksi (1034 MPa). At a yield strength level of 240 ksi (1655 MPa), the K_{Ic} values level off to about 60 ksi·in.$^{1/2}$ (66 MN·m$^{-3/2}$). Wrought plate data of comparable Ni-Cr-Mo steel of somewhat higher carbon content are plotted in Figure 19 to emphasize the strength relationship of K_{Ic} and to demonstrate the comparable performance of cast and wrought products in this area.

Plane strain fracture toughness, like strength, is a temperature sensitive property. Test results in Figures 20 and 21 show examples of the K_{Ic} and yield strength change with temperature for the frequently used cast steels of the C-Mn type (A216, WCC) and the 1.25Cr-0.5Mo-0.2V type. Another plane strain fracture toughness-strength relationship is apparent from the cast Ni-Cr-Mo steel data on the important effect of tempering temperature for quenched steels (Figure 22).

Fracture mechanics tests have the advantage over conventional toughness tests of being able to yield material property values which can be used in design equations (Chapter 4)*. These tests are expensive to perform, however, and interest therefore is strong in empirical correlations between K_{Ic} and the results from quicker, less expensive tests. For Ni-Cr-Mo cast 4335, and Mn-Ni-Cr-Mo cast 9535 type steels room temperature values of K_{Ic} and Charpy V-notch absorbed energy were found to relate according to the equation (9):

$$\left(\frac{K_{Ic}}{\sigma y}\right)^2 = a\frac{E}{\sigma y} + b$$

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TABLE 1 Plane Strain Fracture Toughness of Cast Steels at Room Temperature

Alloy Type	Heat Treatment*	Yield Strength .2% offset ksi	(MPa)	K_{Ic} ksi in.$^{1/2}$	(MNm$^{-3/2}$)	Reference
1.25Cr, .5Mo	SRANTSR	40	(275)	80	(88)	6
CAST 1030	NT	44	(303)	116	(127)	7
A-216, WCC	ATNT	48	(331)	155	(170)	6
.5Cr, .5Mo, .25V	NT	53	(367)	50	(55)	8
13Cr	NT	58	(400)	70	(76)	8
C - 1.5Mn	NT	59	(412)	98	(107)	8
.5C - 1Cr	NT	60	(413)	53	(58)	8
.5 C	NT	61	(425)	59	(65)	8
CAST 9535	NT	89	(614)	61	(67)	9
.35C, .6Ni, .7Cr, .4Mo	NT	99	(683)	58	(64)	8
CAST 4335	SLQT	108	(747)	63	(69)	8
CAST 9536	NT	109	(752)	54	(59)	9
.3C, 1Ni, 1Cr, .3Mo	NT	114	(787)	60	(66)	8
CAST 4335	SLQT	118	(814)	87	(97)	9
CAST 4335	SLQT	126	(869)	85	(93)	9
CAST 4335	SLQT	128	(883)	95	(104)	9
CAST 4335	SLQT	131	(903)	96	(105)	9
CAST 4335	QT	156	(1076)	96	(105)	9
CAST 4335	QT	158	(1090)	105	(115)	9
CAST 4335	QT	169	(1166)	84	(92)	9
CAST 4335	QT	173	(1193)	82	(90)	9
NiCrMo	QT	175	(1207)	89	(98)	10
NiCrMo CAST 4340	QT	175	(1207)	105	(115)	11
Maraging-IN-0180	QT	182	(1255)	120	(132)	11
CAST 4325	QT	183	(1263)	82	(75)	8
CAST 4325	QT	186	(1280)	95	(104)	8
CrMo	QT	200	(1379)	76	(84)	10
NiCrMo CAST 4340	QT	210	(1450)	61	(67)	11
Maraging-230MA	QT	233	(1605)	95	(104)	11
NiCrMo (HY-80 type)	QT	235	(1620)	67	(74)	10
NiCrMo (HY-80 type)	QT	250	(1724)	47	(51)	10

*SR = stress relieved
N = normalized
T = tempered
A = annealed
Q = quenched
SLQ = slack quenched

The constants in the above equation were $a = 2.786$ and $b = 0.090$ when K_{Ic} was expressed in ksi·in.$^{1/2}$, yield strength, σy, in ksi, and absorbed energy, E, in ft·lb. These constants compare well with those for wrought steels (**15,16**). Similar correlations for the room temperature dynamic tear energy of cast steels yielded the constants $a = 0.775$ and $b = -0.279$; however, the term $E/\sigma y$ in the above equation is taken to the one-half power (**9**).

Strength-Fatigue. The most basic method of presenting engineering fatigue data is by means of the S-N curve. The S-N curve relates the dependence of the life of the fatigue specimen, in terms of the number of cycles to failure, N, to the maximum applied stress, S. Additional tests have been used, and the principal findings for cast steel are highlighted in the following sections.

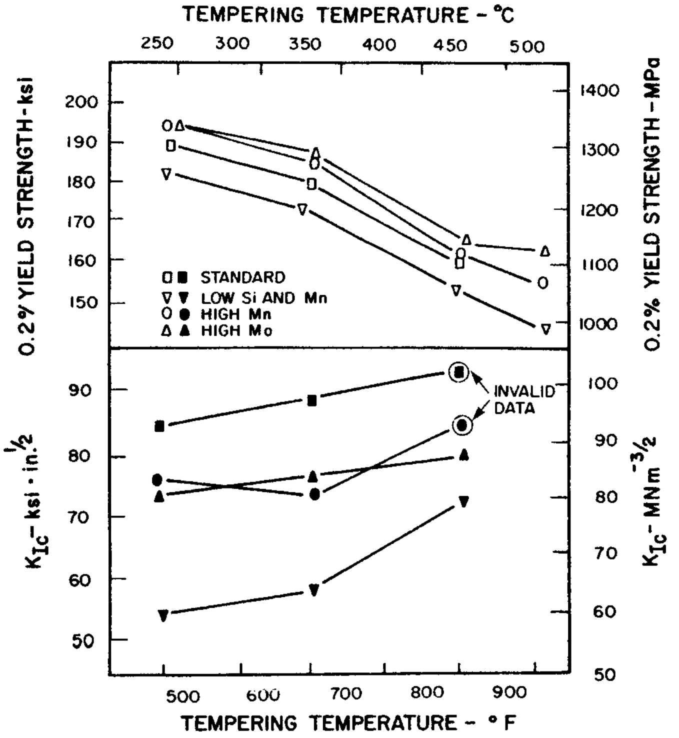


Fig. 22 The effect of tempering temperature on strength and toughness of four heats of 1.5%Ni-Cr-Mo steel after water quenching (**8**).

TABLE 2 Fatigue Properties of Cast Steels (18)

Class[1] and Heat Treatment		Tensile Strength ksi	(MPa)	Yield Strength ksi	(MPa)	Red. in Area %	Elong. %	Hardness BHN	Endurance Limit ksi	(MPa)	Endurance Ratio
						Carbon Steels					
60	A	63	(434)	35	(241)	54	30	131	30	(207)	0.48
65	N	68	(469)	38	(262)	48	28	131	30	(207)	0.44
70	N	75	(517)	42	(290)	45	27	143	35	(241)	0.47
80	NT	82	(565)	48	(331)	40	23	163	37	(255)	0.45
85	NT	90	(621)	55	(379)	38	20	179	39	(269)	0.43
100	QT	105	(724)	75	(517)	41	19	212	45	(310)	0.47
						Alloy Steels[2]					
65	NT	68	(469)	38	(262)	55	32	137	32	(221)	0.47
70	NT	74	(510)	44	(303)	50	28	143	35	(241)	0.47
80	NT	86	(593)	54	(372)	46	24	170	39	(269)	0.45
90	NT	95	(655)	64	(441)	44	20	192	42	(290)	0.44
105	NT	110	(758)	91	(627)	48	21	217	53	(365)	0.48
120	QT	128	(883)	112	(772)	38	16	262	62	(427)	0.48
150	QT	158	(1089)	142	(979)	30	13	311	74	(510)	0.47
175	QT	179	(1234)	160	(1103)	25	11	352	84	(579)	0.47
200	QT	205	(1413)	170	(1172)	21	8	401	88	(607)	0.43

[1] Class of steel based on tensile strength, ksi (MPa). A = Annealed, N = Normalized, NT = Normalized and tempered, QT = Quenched and tempered.

[2] Below 8% total alloy content.

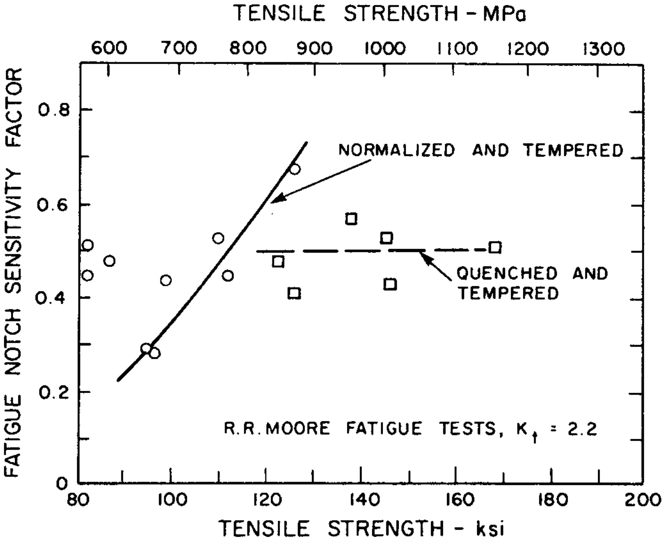
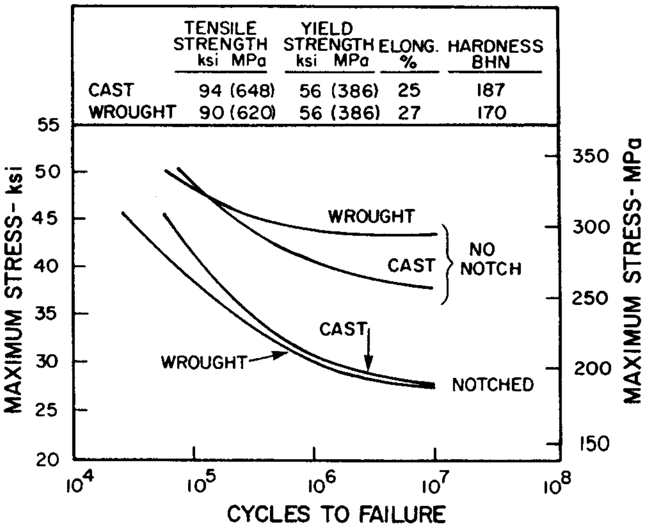


Fig. 23 The fatigue notch sensitivity factor vs. tensile strength for several steels with different heat treatments (**18-24**).



	TENSILE STRENGTH ksi MPa	YIELD STRENGTH ksi MPa	ELONG. %	HARDNESS BHN
CAST	94 (648)	56 (386)	25	187
WROUGHT	90 (620)	56 (386)	27	170

Fig. 24 Fatigue characteristics (S-N curves) for cast and wrought 1040 steel in the normalized and tempered condition, both notched and unnotched (**19**). R. R. Moore rotating beam tests, K_t = 2.2.

Constant Amplitude Tests. The endurance ratio (endurance limit divided by the tensile strength) of cast carbon and low alloy steels, determined in R. R. Moore rotating beam bending fatigue tests (mean stress = 0) is generally taken to be about 0.40 to 0.50 for smooth bars. Data in Table 2 reveal this endurance ratio to be largely independent of strength and whether the steel is plain carbon or low alloy, and whether it has been normalized, normalized and tempered, quenched and tempered, etc. (**17,18**).

The fatigue notch sensitivity, q, determined in rotating beam bending fatigue tests, is related to the microstructure of the steel (composition and heat treatment) and strength. Table 3 shows that the fatigue notch sensitivity factor increases generally with increasing strength, from 0.23 for annealed carbon steel at a tensile strength of 83.5 ksi (577 MPa), to 0.68 for the higher strength normalized and tempered low alloy steels (**18,19**). The quenched and tempered steels with a martensitic structure are less notch sensitive than the normalized and tempered steels with a ferrite-pearlite microstructure (Figure 23). Similar results and trends on notch sensitivity have been reported for tests with sharper notches (**20**). Table 4 reveals remarkably low sensitivity of cast steel to very sharp notches, i.e. to high stress concentration factors.

Cast steel suffers less degradation of fatigue properties due to notches than equivalent wrought steel. When the ideal laboratory test conditions are replaced with more realistic service conditions, the cast steel shows much less notch sensitivity to variations in the values of the test parameters than wrought steel. Table

TABLE 3 Fatigue Notch Sensitivity of Several Cast Steels*(19)

Steel	Tensile Strength		Endurance Limit				Endurance Ratio		Fatigue Notch
			Unnotched		Notched				Sensitivity
Grade	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)	Unnotched	Notched	Factor (q**)
					Normalized and Tempered				
1040	94.2	(648)	37.7	(260)	28	(193)	0.40	0.30	0.29
1330	99.3	(685)	48.4	(334)	31.7	(219)	0.49	0.32	0.44
1330	97	(669)	41.7	(288)	31.2	(215)	0.43	0.32	0.28
4135	112.7	(777)	51.2	(353)	33.3	(230)	0.45	0.30	0.45
4335	126.5	(872)	63	(434)	34.9	(241)	0.50	0.28	0.68
8630	110.5	(762)	54	(372)	33.1	(228)	0.49	0.30	0.53
					Quenched and Tempered				
1330	122.2	(843)	58.5	(403)	37.3	(257)	0.48	0.31	0.48
4135	146.4	(1009)	61.3	(423)	40.6	(280)	0.42	0.28	0.43
4335	168.2	(1160)	77.6	(535)	48.2	(332)	0.46	0.29	0.51
8630	137.5	(948)	64.9	(447)	38.6	(266)	0.47	0.27	0.57
					Annealed				
1040	83.5	(576)	33.2	(229)	26	(179)	0.40	0.31	0.23

*Notched tests run with theoretical stress concentration factor of 2.2.

**q = (K_f −1)/(K_t −1), K_f = Notch fatigue factor = Endurance limit unnotched/Endurance limit notched, K_t = Theoretical stress concentration factor

TABLE 4 Fatigue Notch Sensitivity of Cast 8630 Steel (20)

Heat Treatment	Tensile Strength ksi	(MPa)	Notch Radius in.	(mm)	Stress Concentration Factor	Fatigue Notch Sensitivity Factor(q)
Norm & Temper	83.1	(573)	0.015	(.381)	2.2	0.45
Norm & Temper	83.4	(575)	0.015	(.381)	2.2	0.51
Norm & Temper	87.3	(602)	0.015	(.381)	2.2	0.48
Quench & Temper	126.0	(869)	0.015	(.381)	2.2	0.41
Quench & Temper	145.0	(1000)	0.015	(.381)	2.2	0.53
Anneal	88.9	(613)	0.001	(.025)	6.2	0.14
Quench & Temper	132.0	(910)	0.001	(.025)	6.2	0.22

*q = (K_f −1)/(K_t −1), K_f = Notch fatigue factor = Endurance limit unnotched/Endurance limit notched, K_t = Theoretical stress concentration factor

5 shows the wrought steel to be 1.5 to 2.3 times as notch sensitive as cast steel. Under the ideal laboratory test conditions and test preparation (uniform section size, polished and honed surfaces, etc.), the endurance limit of wrought steel is higher. The same fatigue characteristics as those of cast steel, however, are obtained when a notch is introduced, or when standard lathe-turned surfaces are employed in the rotating beam bending fatigue test (**19, 25**). These effects are illustrated in Figures 24 through 27.

The cyclic stress-strain characteristics in Figure 28 and Table 6 show a reduction of the strain hardening exponent of the normalized and tempered cast carbon steel (SAE 1030) from $n = 0.3$ in monotonic tension to $n' = 0.13$ under cyclic strain controlled tests (7).

The strain life characteristics of normalized and tempered cast carbon steel (SAE 1030) and wrought steel are similar as exhibited in Figure 29 and Table 7 for strain controlled constant amplitude low cycle fatigue tests (0.001 to 0.02 strain range amplitudes, with constant strain rate triangle wave form of 2.5 x 10 $^{-4}$/sec at 0.5 to 3.3 Hz) (7).

Constant load amplitude fatigue crack growth properties for load ratios $R = 0$ indicate comparable properties for cast and wrought steel (Figure 30), and slightly better properties for normalized and tempered cast carbon steel (SAE 1030) under load ratios of $R = -1$. These tests were conducted in air at 10 to 30 Hz depending on load ratio, initial stress intensity, and crack length. Additional crack propagation rate data are listed in Table 8 for normalized and tempered cast steels used in the pressure vessel and power generating industry and for a variety of cast carbon and low alloy steels.

Variable Amplitude Tests. Variable load amplitude fatigue test using the T/H SAE service spectrum (Figure 31) and a modified transmission history which eliminates all compressive loading indicate equal total life for cast and wrought carbon steel (cast SAE 1030 and wrought SAE 1020, respectively) (Figure 32). The slower crack growth rate in the cast material compensated for the longer crack initiation life [$a = 0.01$ in. (0.25 mm)] of the wrought carbon steel.

The total fatigue life is further comparable for the cast and wrought carbon steels with and without the appliation of tensile overloads (Po/P max = 1.6) as indicated in Figure 33. Removal of the compressive loads from the T/H spectrum increases crack initiation life by a factor of 3 and crack propagation life by a factor of 2. The compressive loads are therefore detrimental to both crack initiation and crack propagation. Tensile overloads increase total life but have mixed effects on crack initiation and propagation in these variable load amplitude fatigue tests (7).

TABLE 5 Fatigue Notch Sensitivity Factors for Cast and Wrought Steels at a Number of Strength Levels (18)

Steel	Tensile Strength ksi	(MPa)	Fatigue Notch Sensitivity Factor (q)*
	Annealed		
1040 Cast	83.5	(576)	0.23
1040 Wrought	81.4	(561)	0.43
	Normalized and Tempered		
1040 Cast	94.2	(649)	0.29
1040 Wrought	90.0	(620)	0.50
1330 Cast	97.0	(669)	0.28
1340 Wrought	101.8	(702)	0.65
4135 Cast	112.7	(777)	0.45
4140 Wrought	111.1	(766)	0.81
4335 Cast	126.5	(872)	0.68
4340 Wrought	124.6	(859)	0.97
8630 Cast	110.5	(762)	0.53
8640 Wrought	108.5	(748)	0.85
	Quenched and Tempered		
1330 Cast	122.2	(843)	0.48
1340 Wrought	121.2	(836)	0.73
4135 Cast	146.4	(1009)	0.43
4140 Wrought	146.8	(1012)	0.93
4335 Cast	168.2	(1160)	0.51
4340 Wrought	168.4	(1161)	0.92
8630 Cast	137.5	(948)	0.57
8640 Wrought	138.2	(953)	0.90

*$q = (K_f - 1)/(K_t - 1)$

K_f = Notch fatigue factor = Endurance limit unnotched/Endurance limit notched

K_t = Theoretical stress concentration factor

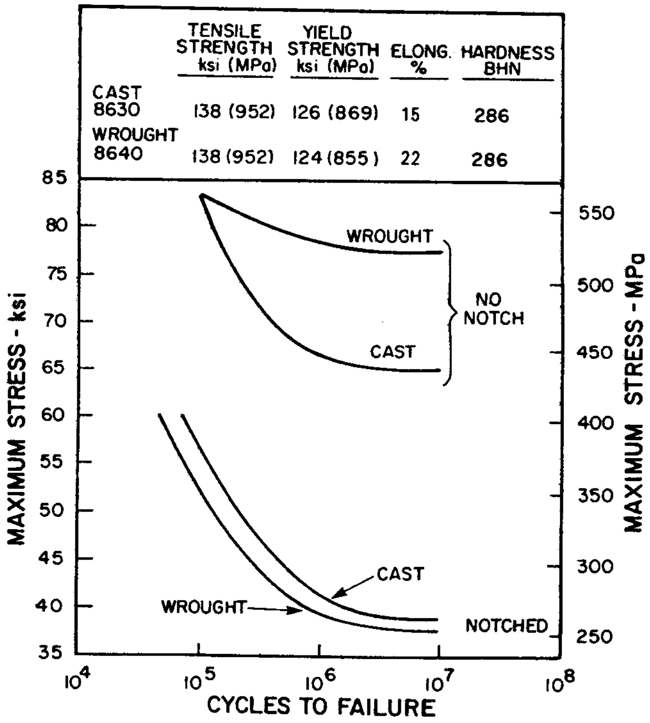


Fig. 25 Fatigue characteristics (S-N curves) for cast and wrought 8600 series steels, quenched and tempered to the same hardness, both notched and unnotched (19). R. R. Moore rotating beam tests, $K_t = 2.2$.

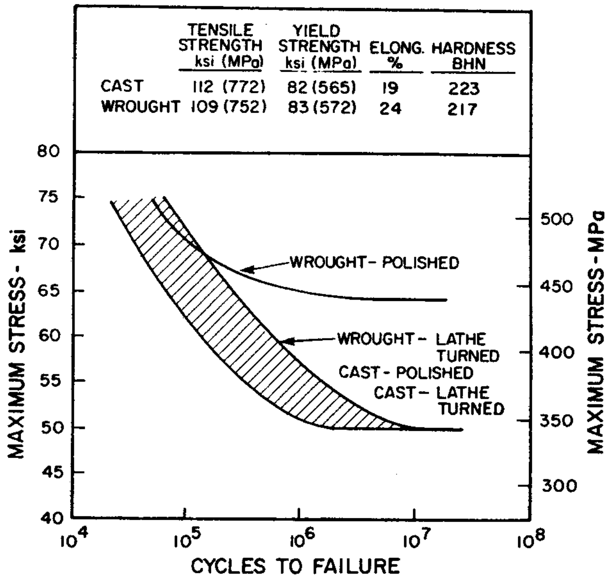


Fig. 26 Comparison of the fatigue characteristics (S-N curves) of a cast and a wrought 8640 steel of the same composition and strength, quenched and tempered, with standard machine finish and with hand-polished finish (19). R. R. Moore rotating beam tests. The polished specimens were first ground, then hand lapped. The lathe-turned specimens received standard machine finish.

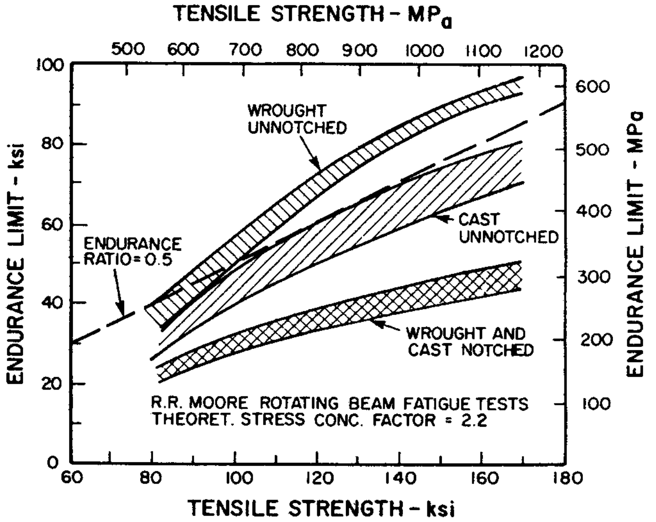


Fig. 27 Relation between fatigue endurance limit (both notched and unnotched) and unnotched tensile strength for a number of cast and wrought steels with various heat treatments (19).

TABLE 6 Monotonic Tensile and Cyclic Stress Strain Properties (7)

Monotonic Tension

Property	Cast SAE1030		Wrought SAE1020	
0.2% yield strength, σ_y—ksi (MPa)	44	(303)	38	(262)
Ultimate strength, σ_u—ksi (MPa)	72	(496)	60.0	(413)
True fracture strength, σ_f—ksi (MPa)	109	(750)	145	(999)
Reduction in area—%	46		58	
True fracture ductility, ε_f	0.62		0.87	
Modulus of elasticity, E—psi (GPa)	30×10^6	(207)	29.5×10^6	(203)*
Strain hardening exponent, n	0.3		0.19*	
Strength coefficient, K, ksi (MPa)	158	(1090)	107	(738)*

Cyclic Stress-Strain

Property	Cast SAE 1030		Wrought SAE 1020	
0.2% yield strength, σ_y'—ksi (MPa)	46	(317)	35	(241)*
Strength coefficient, K'—ksi (MPa)	103	(708)	112	(772)*
Strain hardening exponent, n'	0.13		0.18*	

*Representative values taken from Ref. 26

TABLE 7 Constant Amplitude Fatigue Properties (7)

Strain Control Fatigue Properties

Property	Cast SAE 1030	Wrought SAE 1020
Fatigue strength coefficient, σ_f'—ksi (MPa)	95 (653)	130 (896)*
Fatigue strength exponent, b	−0.082	−0.12*
Fatigue ductility coefficient, ε_f'	0.28	0.41*
Fatigue ductility exponent, c	−0.51	−0.51*

*Representative values taken from Ref. (29).

Fatigue Crack Growth Rate Properties

	1030 Cast Steel		1020 Wrought Steel	
Property	$R \approx 0$	$R = -1$	$R \approx 0$	$R = -1$
A using ksi $\sqrt{\text{in.}}$ and in.	1.24×10^{-11}	1.88×10^{-11}	$.372 \times 10^{-11}$	6.76×10^{-11}
A (using MPa $\sqrt{\text{m}}$ and m)	2.2×10^{-13}	3.14×10^{-13}	$.64 \times 10^{-13}$	12.29×10^{-13}
n	3.82	4.45	4.18	3.54

*Reference 26.

TABLE 8 Crack Propagation Rate Characteristics of Carbon and Low Alloy Steels

Alloy Type	Heat Treatment*	.2% YS		K_{Ic}		A**	n**	Ref. No.***
		ksi	(MPa)	ksi.in.$^{1/2}$	(MNm$^{-3/2}$)	using MNm$^{-3/2}$	and m	
1-1/2Mn	A,N	62	(427)	126	(138)	$10^{-7.00}$	2.07	8
1-1/2Cr-1/2Mo-1/4V	A,N,T,	73	(503)	42	(46)	$10^{-6.55}$	2.11	8
1-1/2Mn-Mo	A,WQ,TT	96	(662)	114	(125)	$10^{-7.10}$	1.94	8
1-1/2Ni-1Cr-1/3Mo	A,OQ,T	123	(848)	73	(80)	$10^{-6.71}$	1.80	8
.54C	A	52	(359)	78	(86)	$10^{-6.91}$	2.09	8
						using ksi·in.$^{1/2}$ and in.		
1-1/4Mn(A216,WCC)	A,N,T	48	(331)	116	(127)	2.3×10^{-19}	3.00	6
1-1/4Cr-1/2Mo	SR,A,N,T,SR	40	(276)	80	(88)	3.1×10^{-24}	4.10	6
0.25C	N,T	43	(296)	—	—	1.69×10^{-10}	3.3	27
0.35C	N,T	73	(503)	—	—	1.69×10^{-10}	3.3	27
0.35C	N,T	88	(607)	—	—	1.69×10^{-10}	3.3	27
1.53C	SA	66	(455)	—	—	1.69×10^{-10}	3.3	27
1.53C	N,T	63	(434)	—	—	1.3×10^{-10}	5.0	27

*A = Annealed
N = Normalized
T = Tempered, TT = Double tempered
WQ = Water quenched, OQ = Oil quenched
SR = Stress relieved
SA = Spheroidize-anneal

**The values for A and n denote material constants in the expression for crack propagation $da/dN = A\Delta K^n$

***R = 0 for References 6 and 8, tests conducted in air, at room temperature, at 20 Hz for Reference 8, and at 600 Hz for Reference 6.
R = 0.1, 0.5, and 0.7 for Reference 27, conducted in air, at room temperature, at 300 Hz.

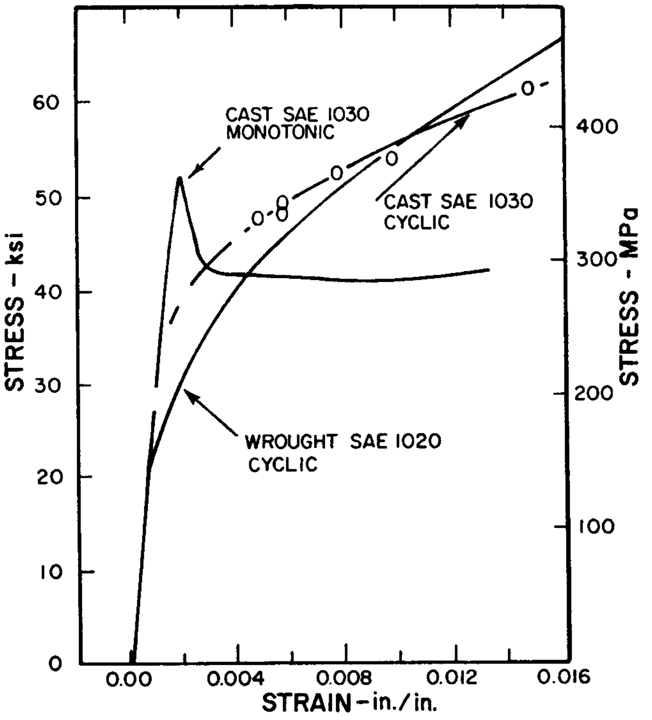


Fig. 28 Monotonic tensile and cyclic stress-strain behavior of comparable wrought and cast carbon steel in the normalized and tempered condition (7).

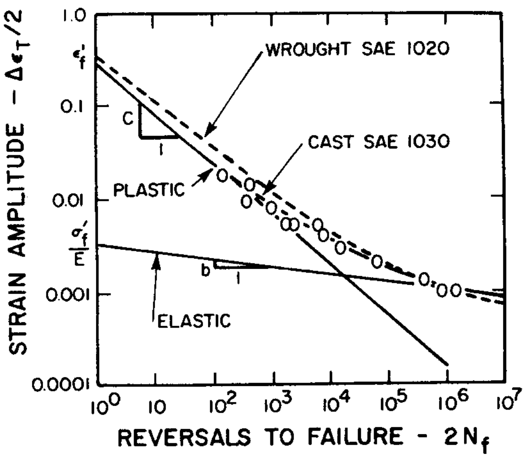


Fig. 29 Low cycle strain-control fatigue behavior of comparable cast and wrought carbon steel in the normalized and tempered condition (7).

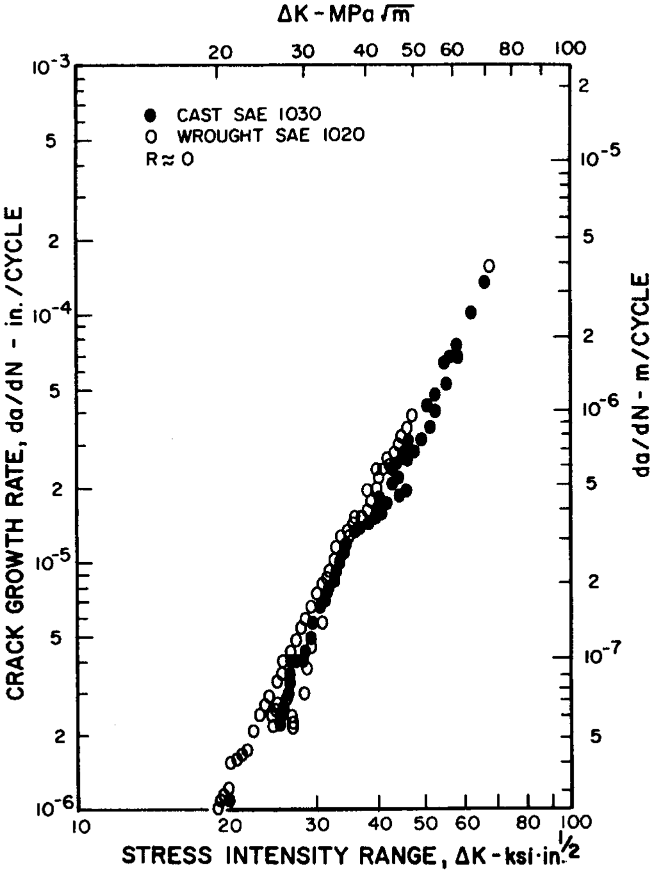


Fig. 30a Constant amplitude fatigue crack growth behavior of comparable cast and wrought carbon steel in the normalized and tempered condition, $R \approx 0$ (7).

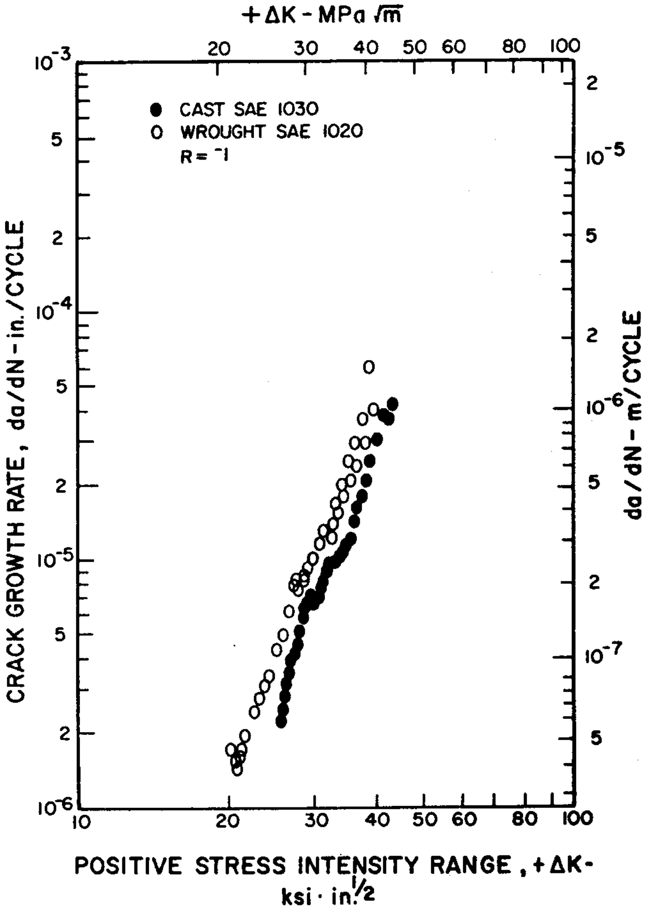
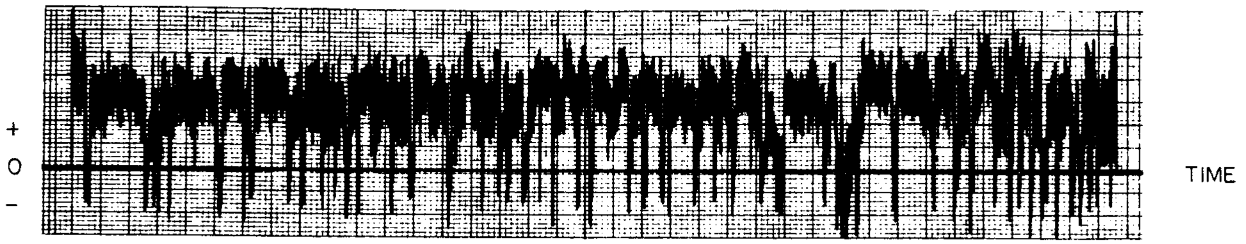
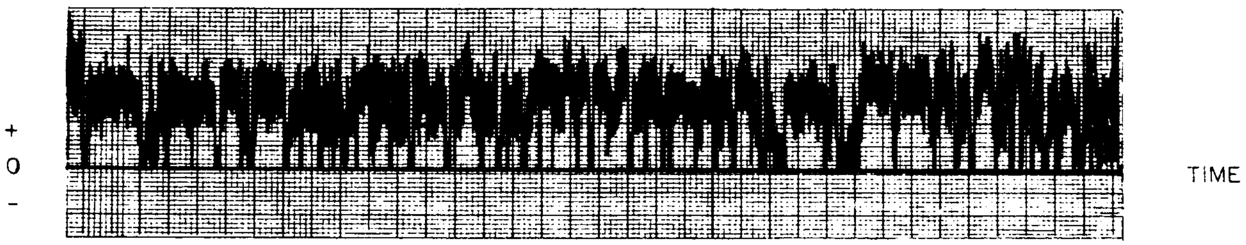


Fig. 30b Constant amplitude fatigue crack growth behavior of comparable cast and wrought carbon steel in the normalized and tempered condition, $R = -1$ (7).



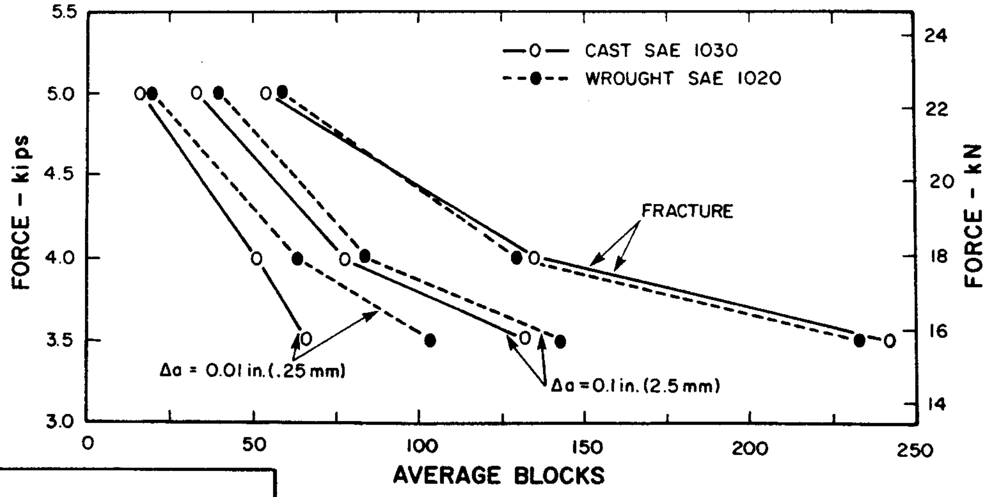
A. T/H 1,708 REVERSALS



B. MOD T/H 1,692 REVERSALS

Fig. 31 Variable amplitude load Spectra T/H and mod T/H (7).

Fig. 32 Average blocks to specific crack lengths and fracture with T/H load history of comparable cast and wrought carbon steel in the normalized and tempered condition (7).



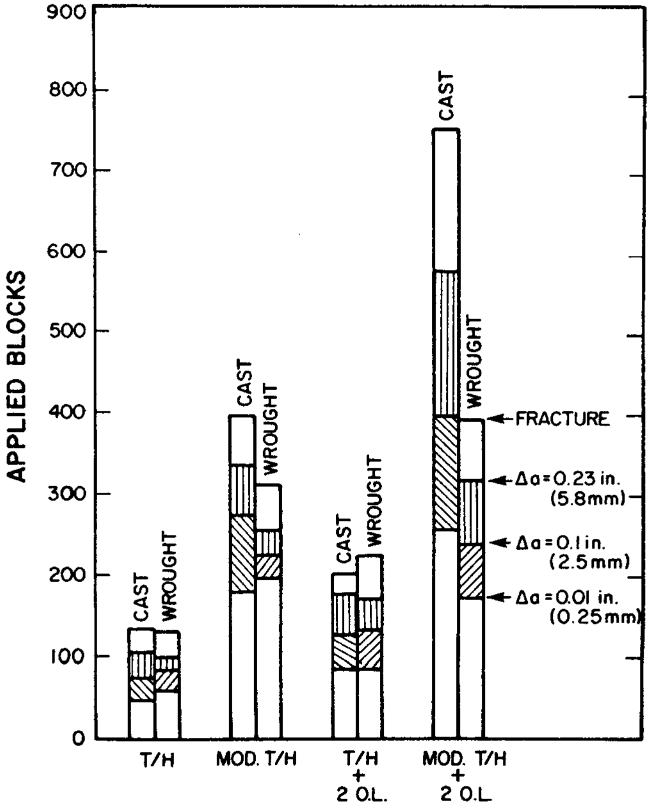


Fig. 33 Average blocks to specific crack lengths and fracture with four load histories of comparable cast and wrought carbon steel in the normalized and tempered condition, P max = 4 kips (17.8 kN) (7).

Section Size, Mass Effects

Mass effects are common to steels, whether rolled, forged, or cast, because the cooling rate during the heat treating operation varies with section size, and because the microstructure components, grain size, and nonmetallic inclusions, increase in size from surface to center. These changes in microstructure are illustrated in Figures 34 through 36. Mass effects are metallurgical in nature, distinct from the effect of discontinuities. An example of how the mass of a component lowers strength properties for wrought AISI 8630 and for AISI 8650 steel plate is shown in Figures 37a and 37b. Properties are plotted for the 1/4 T location, halfway between surface and center of plate. Comparison of Figures 37a and 37b indicates that toughness is proportional to strength only in a limited way and that a major loss in toughness may occur in heavier sections.

The section size, or mass effect, is of particular importance to steel castings because the mechanical properties are typically assessed from test bars machined from standardized coupons which have fixed dimensions and are cast separately from or attached to the castings (Figure 38). To remove test bars from the casting is impractical because removal of material for testing would destroy the usefulness of the component or require costly weld repairs to replace the material removed for testing purposes.

One cannot routinely expect that test specimens removed from a casting will exhibit the same properties as test specimens machined from the standard test coupon designs for which minimum properties are established in specifications. The mass effect discussed above, i.e. the differences in cooling rate between that of test coupons and of the part being produced, is the funda-

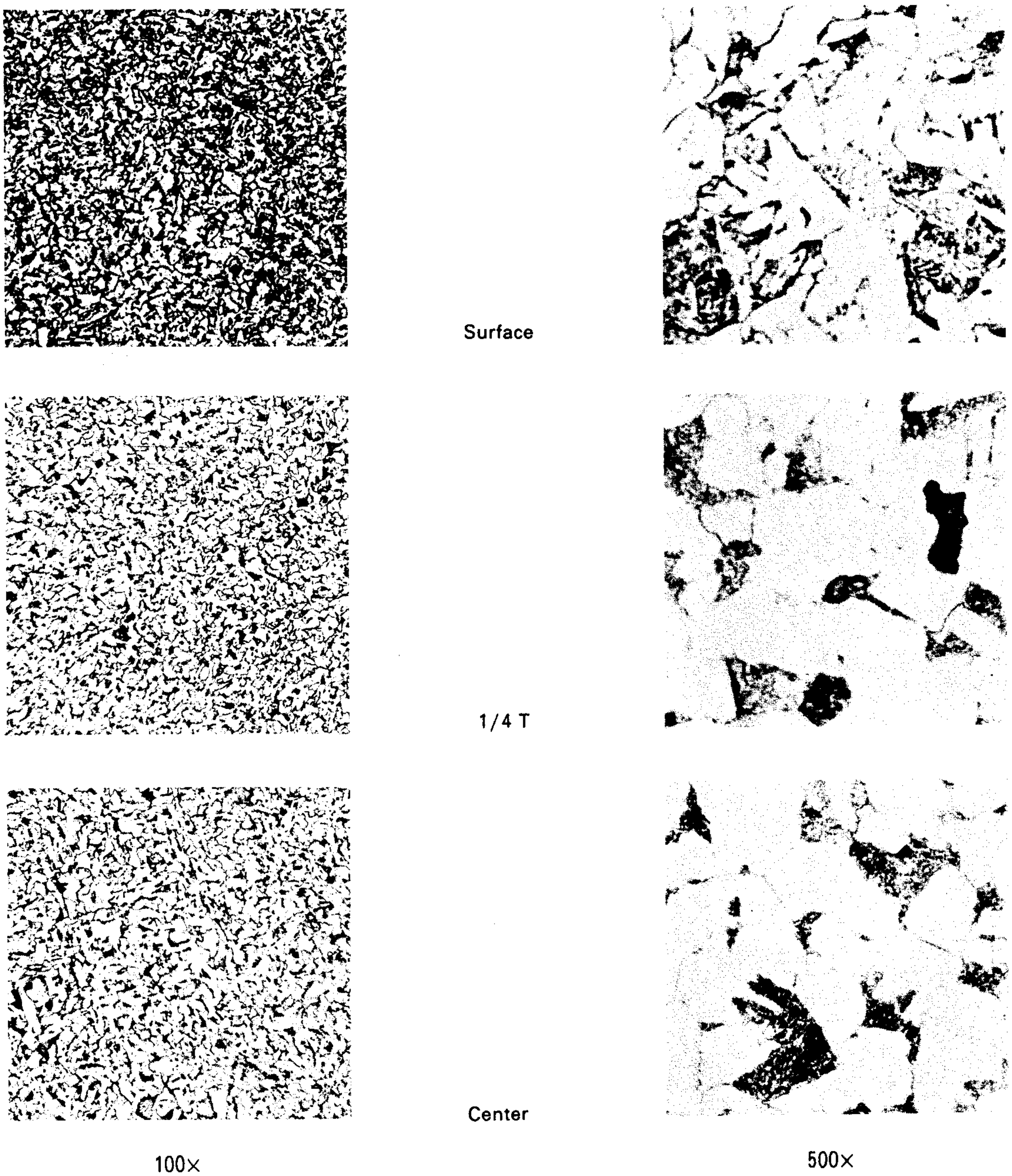


Fig. 34 The ferrite-pearlite structure of a quenched and tempered 4-in. (102 mm) thick, A-216-WCC type, carbon steel plate casting.

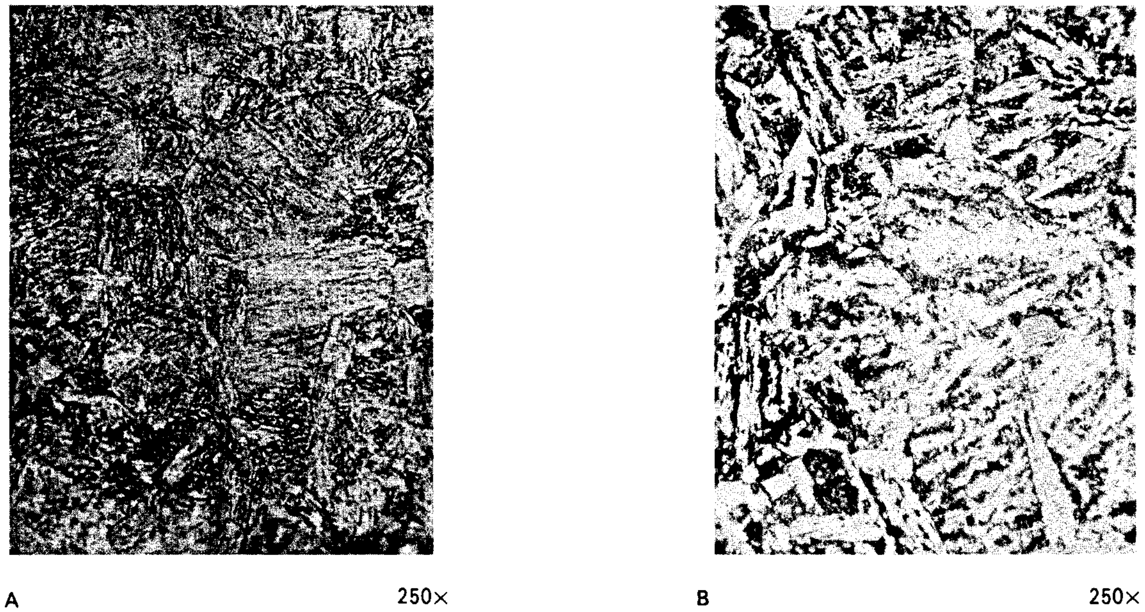


Fig. 35 A. The martensitic microstructure at the surface of a quenched and tempered Ni-Cr-Mo (cast 8635) 17-in. (432 mm) thick gear blank. B. The acicular, ferrite-pearlite structure of the casting in A—at the center of the 17-in. (432 mm) thick section.

Representative
Properties:

	UTS		YS		El	RA	BHN	C_v – Impact Energy at RT	
	ksi	MPa	ksi	MPa	%	%		ft·lb	J
A	160	1103	146	1007	14	38	345	30	41
B	110	758	—	—	2	2	280	4	5

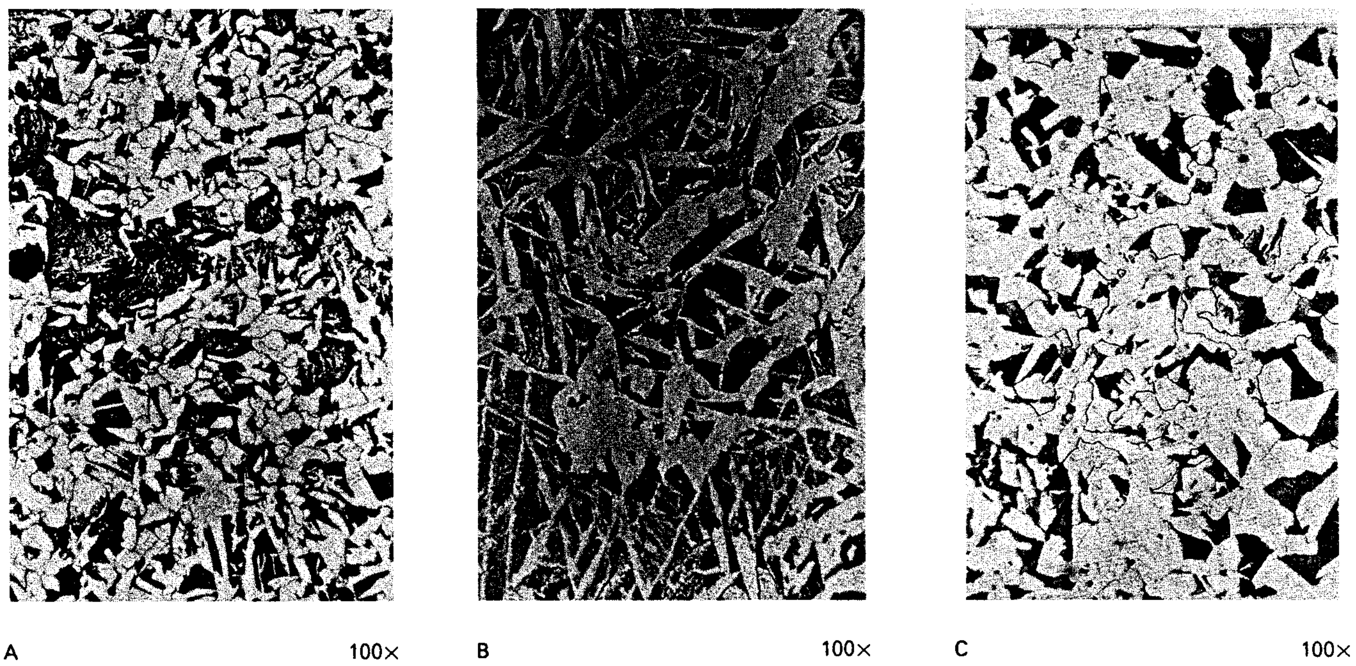


Fig. 36 A. Ferrite-pearlite structure—representation in a 1.5-in. (38 mm) section of a larger 15-ton, 2% Ni, .20% C steel turbine blade casting that was normalized and tempered. B. Same as in A, but coarser and acicular Widmanstatten structure in the center of a 7-in. (178 mm) thick portion of the same casting. C. Same as in B, but coarse and blocky in appearance in the center of a 28-in. (711 mm) thick portion of the same casting.

Representative	UTS		YS		El	RA	BHN	C_v – Impact Energy at RT	
Properties:	ksi	MPa	ksi	MPa	%	%		ft·lb	J
A	80	552	49	338	26	55	165	58	79
B	76	524	47	324	25	52	155	56	76
C	75	517	46	317	22	38	148	57	77

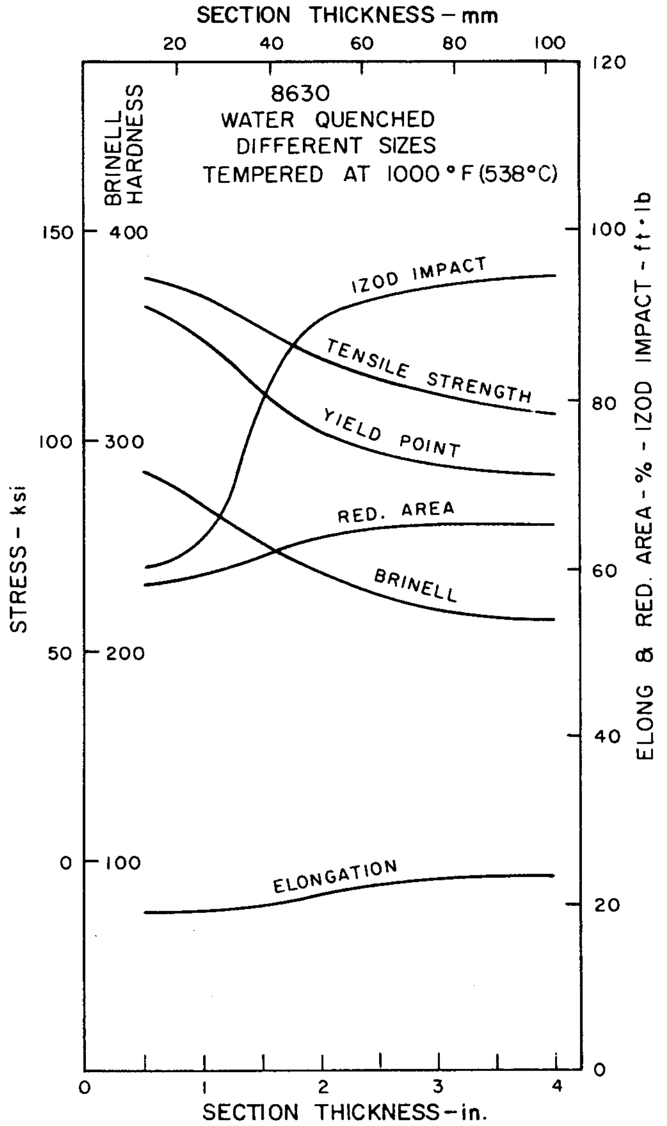


Fig. 37a Section size effects on water quenched and tempered wrought AISI 8630 steel in sizes over 1 in. (25 mm). The properties reported are those midway between surface and center (Conversion: 1 ksi = 6.8948 MPa, 1 ft·lb = 1.356 J) (**28**).

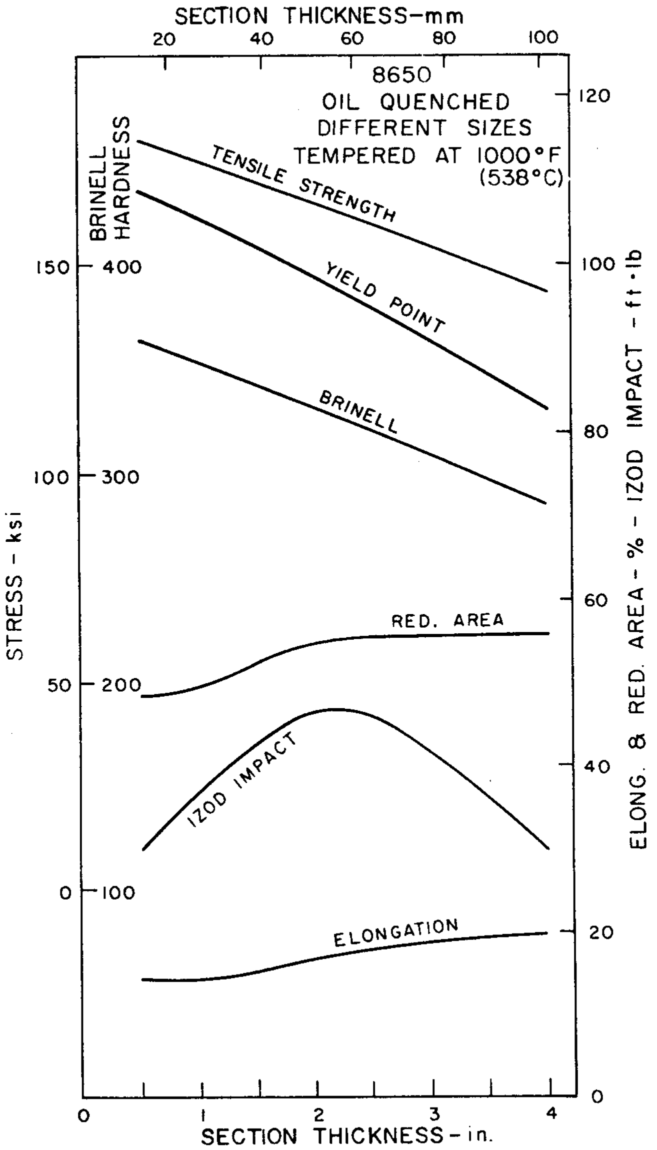


Fig. 37b Section size effects on oil quenched and tempered wrought AISI 8650 steel. In sizes over 1 in. (25 mm), the properties reported are those midway between surface and center (Conversion: 1 ksi = 6.8948 MPa, 1 ft. lb = 1.356 J) (**28**).

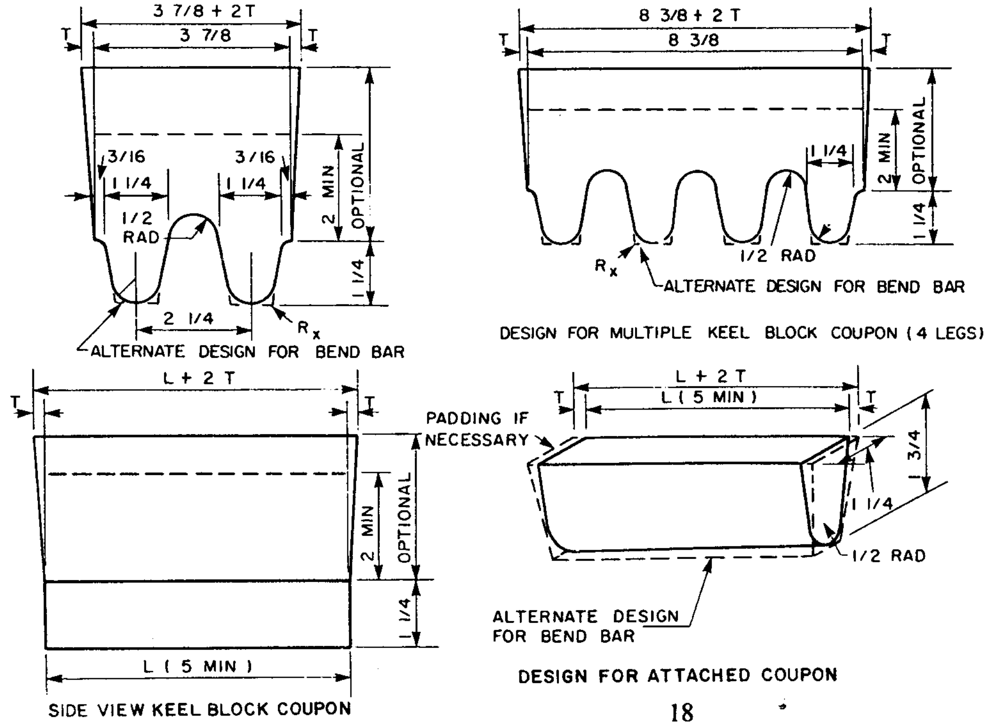


Fig. 38 Keel block coupon (ASTM A370—Mechanical testing of steel products).

mental reason for this situation. Several specifications provide for the mass effect by permitting the testing of coupons which are larger than the basic keel block in Figure 38, and whose cooling rate is therefore more representative of that experienced by the part being produced. Among these specifications are ASTM specifications E208, A356, and A757.

Alloy and Heat Treatment Influence on Section Size Effects. The tensile properties of normalized and tempered cast carbon steel with 0.3% C (cast 1030) and Ni-Cr-Mo low alloy steel (cast 8635) in Figures 39a and 39b reveal the largest effect of section size to be on reduction of area. The higher strength of the low alloy steel is relatively uniform in the 1.25 and 3-in. (32 and 76 mm) sections. For the 6-in. (152 mm) section a distinct drop in yield and tensile strength is evident. These section size effects on tensile properties are more pronounced upon quenching and tempering to higher strength values as evident from data illustrated in Figure 40 for Ni-Cr-Mo low alloy cast 8635 steel.

Toughness, because of its sensitivity to the changes in metallurgical structure, i.e. heat treatment, may reveal major effects of section size. Figure 41 shows the differences in Charpy V-notch impact energy due to section size as well as the variation of impact energy with location in a given section. These data shown only minor effects for the normalized and tempered steels. Comparable and uniform properties are also shown for the higher strength, quenched and tempered cast 8630 steel up to a 3-in. (76 mm) section thickness. For the 6-in. (152 mm) thick 8630 steel a significant loss in toughness occurs due to insufficient hardenability of the steel. Lack of hardenabilty of this steel prevents the 6-in. (152 mm) section from through hardening and forming a sufficient amount of martensite at distances of 1 in. (25 mm) or more below the surface of the 6-in. (152 mm) thick section.

Fatigue strength values are affected by the mass effect in a manner similar to tensile strength. When the endurance limit is "normalized" for tensile strength by dividing the endurance limit by the tensile strength, the resulting endurance ratio reveals only minor effects of section size as illustrated in Figure 42.

Early studies of the section size effect (**19, 29, 30**) evaluated mechanical properties extensively as a function of location in a given casting to determine the rate of change with distance from the surface to the center of the casting.

Figure 43 illustrates one example of these studies and demonstrates the tendency of properties to level off at distances of approximately 1/4 thickness, 1/4 T, from the surface. Newer studies, therefore, tend to be limited to the 1/4 T location. Data of this type in Table 9 illustrate the trends for property changes as a function of section size. These data do not reflect minimum values to be expected for the grades listed. Table 10 shows the compositions of the grades listed in Table 9.

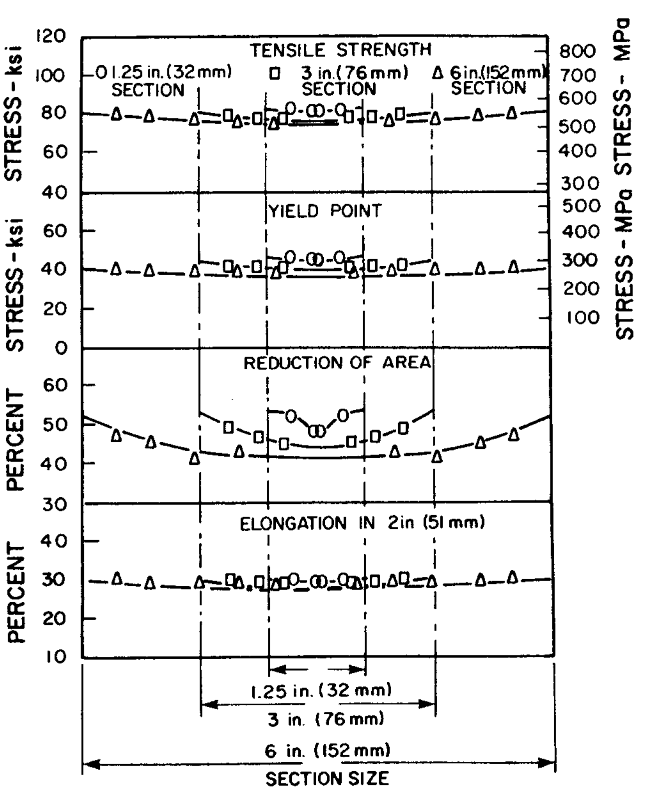


Fig. 39a Distribution of tensile properties of cast 1030 steel. Normalized from 1600°F (871°C) and tempered at 1200°F (649°C) (**19**).

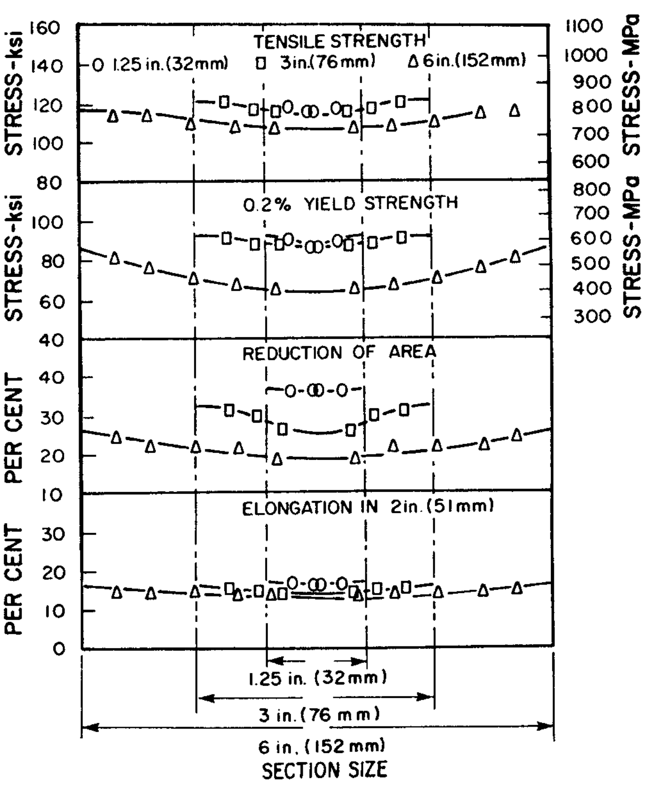


Fig. 39b Distribution of tensile properties of cast 8635 steel. Normalized from 1600°F (871°C) and tempered at 1200°F (649°C) (**19**).

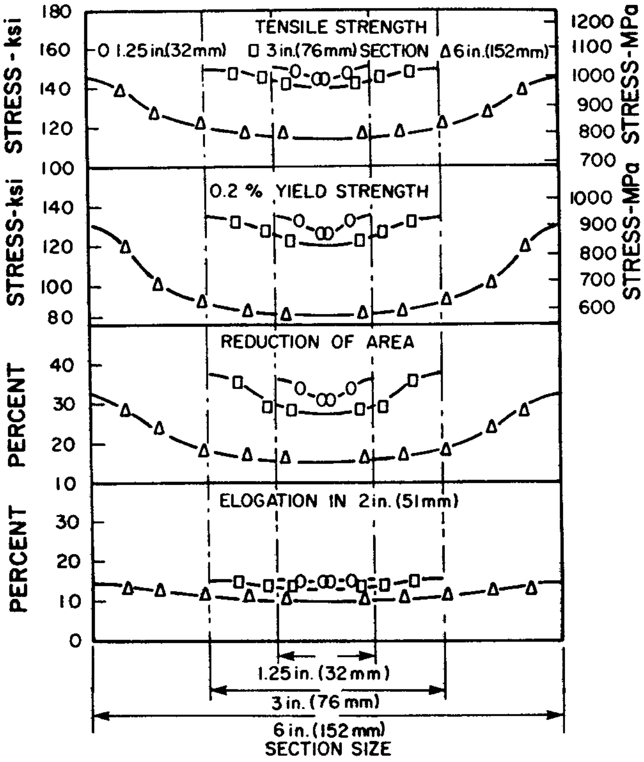


Fig. 40 Distribution of tensile properties of cast 8635 steel. Water quenched from 1500°F (816°C) and tempered at 1100°F (593°C) (**19**).

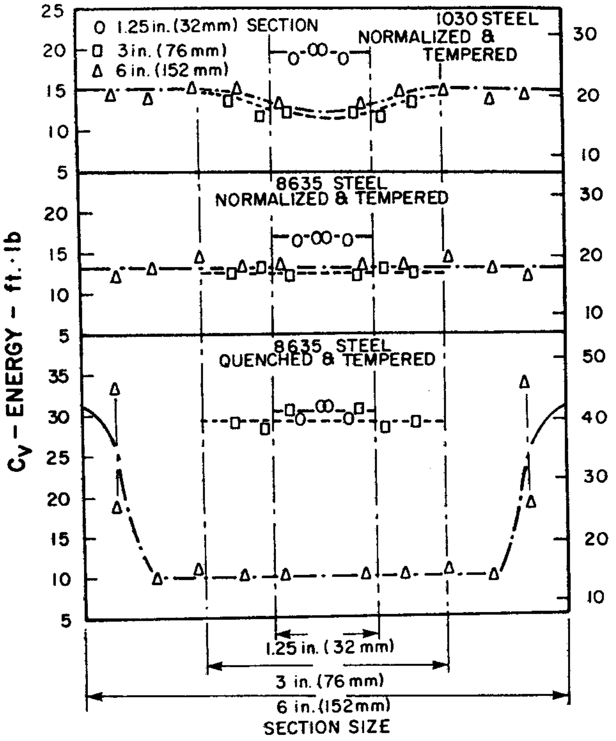


Fig. 41 Distribution of Charpy V-notch impact properties at 74°F (23°C) for various section sizes of cast steels (**19**).

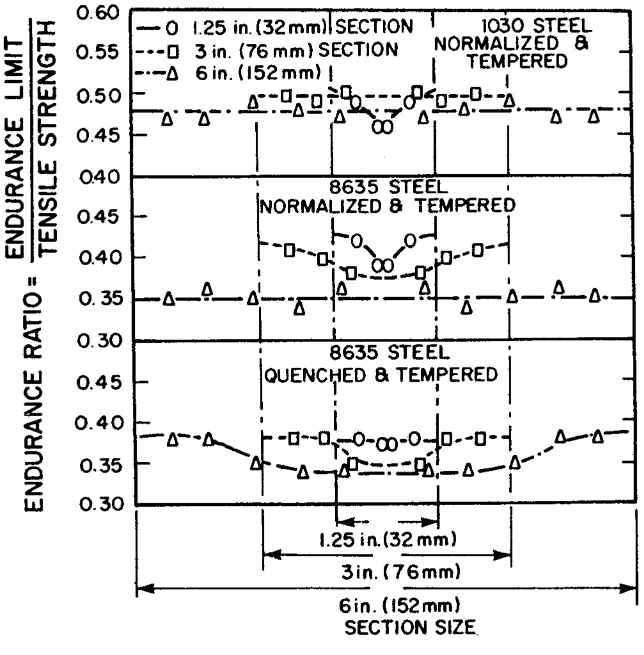


Fig. 42 Distribution of endurance ratio for various section sizes of cast steels (**19**).

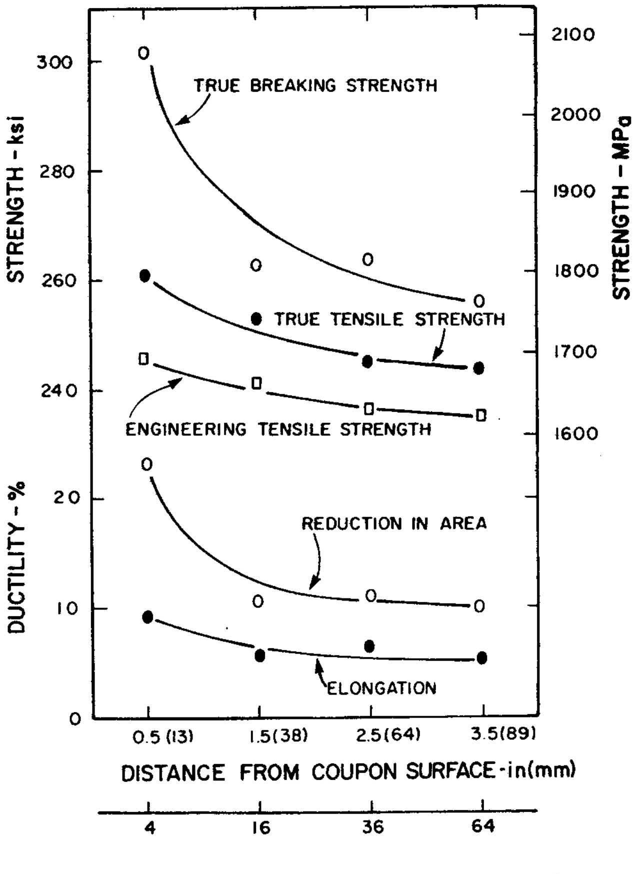


Fig. 43 Effect of mass on tensile properties in 8-in. (203-mm) coupon of cast Ni-Cr-Mo, 4330 steel in the quenched and tempered condition (**29**).

TABLE 9 Tensile and Low Temperature Toughness Properties[A] of Selected Ferritic Hardenable Cast Steels[B]

ASTM Spec.	ASTM Grade	Heat Treatment[C]	Section Size in.	(mm)	UTS ksi	(MPa)	Y.S. ksi	(MPa)	EL %	R.A. %	$FATT_{50}$ °F	(°C)	TCV-15 °F	(°C)	NDTT °F	(°C)	Reference
A217	WCA	NT	1	(25)	75	(517)	47	(324)	20	46	68	(20)	27	(−3)	5	(−15)	31
			3	(51)	75	(517)	45	(310)	28	38	116	(46)	−4	(−20)	14	(−10)	
			5	(76)	72	(496)	40	(276)	22	48	32	(0)	0	(−18)	32	(0)	
	WCB	NT	1	(25)	73	(503)	45	(310)	29	25	93	(34)	59	(15)	0	(−18)	31
			3	(51)	74	(510)	49	(338)	17	20	134	(57)	32	(0)	9	(−13)	
			5	(76)	71	(490)	46	(317)	13	18	131	(55)	57	(14)	14	(−10)	
	WCC	NT	1	(25)	75	(517)	53	(365)	20	18	61	(16)	−4	(−20)	7	(−14)	31
			3	(51)	75	(517)	54	(372)	16	15	39	(4)	14	(−10)	−4	(−20)	
			5	(76)	74	(510)	52	(359)	16	13	55	(13)	23	(−5)	0	(−18)	
A352	LCB	QT	1	(25)	70	(483)	46	(317)	35	73	20	(−4)	−75	(−60)	—	—	32
			3	(51)	65	(448)	43	(296)	39	73	60	(16)	−40	(−40)	−40	(−40)	
			5	(76)	65	(448)	42	(290)	35	60	60	(16)	−30	(−34)	−40	(−40)	
	LCC	QT	1	(25)	76	(524)	53	(365)	18	29	37	(3)	−73	(−58)	−40	(−40)	31
			3	(51)	77	(531)	51	(352)	28	47	41	(5)	−67	(−55)	−22	(−30)	
			5	(76)	71	(490)	49	(338)	28	49	36	(2)	−40	(−40)	−13	(−25)	
	LC1	QT	1	(25)	80	(552)	65	(448)	28	62	14	(−10)	−86	(−66)	−40	(−40)	31
			3	(51)	79	(545)	66	(445)	29	64	32	(0)	−58	(−50)	−22	(−30)	
			5	(76)	74	(510)	53	(365)	25	44	57	(14)	0	(−18)	5	(−15)	
	LC2	QT	1	(25)	77	(531)	62	(427)	26	35	−78	(−61)	−160	(−107)	−121	(−85)	32
			3	(51)	73	(503)	59	(407)	33	48	−47	(−44)	−166	(−110)	−112	(−80)	
			5	(76)	71	(490)	55	(379)	30	54	−22	(−30)	−144	(−98)	−94	(−70)	
A352	LC2-1	QT	1	(25)	109	(752)	97	(670)	24	65	−60	(−51)	−140	(−96)	—	—	32
			3	(51)	106	(731)	92	(634)	23	66	−55	(−49)	−95	(−71)	−140	(−96)	
			5	(76)	107	(738)	93	(641)	21	53	−25	(−32)	−110	(−79)	−80	(−62)	
	LC3	QT	1	(25)	89	(614)	57	(393)	19	33	−121	(−85)	−166	(−110)	−193	(−125)	31
			3	(51)	92	(634)	61	(421)	17	25	−193	(−125)	−157	(−105)	−175	(−115)	
			5	(76)	85	(586)	60	(413)	15	18	−202	(−130)	−148	(−100)	−193	(−125)	
A757	C1Q	NQTA	1	(25)	95	(655)	72	(496)	27	60	—	—	−130	(−90)	—	—	33
			3	(51)	92	(634)	69	(476)	31	70	—	—	−120	(−84)	−90	(−68)	
			5	(76)	78	(738)	60	(413)	25	54	—	—	−105	(−76)	−80	(−62)	
	C1Q	ANQT	3	(51)	82	(565)	68	(469)	30	58	-15	(-26)	-110	(-79)	-85	(-65)	33
			5	(76)	83	(572)	62	(427)	28	55	-22	(-30)	-85	(-65)	-68	(-56)	
	E1Q	NQT	1	(25)	102	(703)	90	(621)	26	69	—	—	−145	(−99)	−175	(−115)	33
			3	(51)	102	(703)	88	(607)	22	53	—	—	−120	(−84)	−140	(−96)	
			5	(76)	99	(683)	83	(572)	25	69	—	—	—	—	−100	(−73)	
	E1Q	ANQT	3	(51)	90	(621)	72	(496)	28	62	-120	(-84)	-188	(-122)	-151	(-102)	33
			5	(76)	91	(627)	71	(490)	23	61	-100	(-73)	-155	(-104)	-144	(-98)	
	E3N[D]	QT	1	(25)	132	(910)	117	(807)	8	20	−184	(−120)	−256	(−160)	−211	(−135)	31
			3	(51)	127	(816)	87	(600)	17	49	−157	(−105)	−220	(−140)	−202	(−130)	
			5	(76)	117	(807)	95	(655)	10	14	−94	(−70)	−148	(−100)	−202	(−130)	

[A] Determined at the 1/4 Thickness Location of Cast Plates Measuring in excess of 4T × 4T.

[B] See Table 10 for Composition and Heat Treatment.

[C] N = Normalized, Q = Quenched, A = Aged, T = Tempered

[D] Also referred to as CA-6NM, as in ASTM A487.

TABLE 10 Composition of Selected Ferritic Hardenable Cast Steels[A]

ASTM		Heat	Composition—%								
Specification	Grade	Treatment[B]	C	Mn	Si	P	S	Cr	Ni	Mo	Al
216	WCA	NT	.24	.72	.53	.021	.013	—	—	—	—
	WCB	NT	.24	.65	.42	.012	.023	.15	.09	.07	.044
	WCC	NT	.21	1.12	.51	.034	.035	.10	.09	.047	—
352	LCB	WQTSR	.18	.75	.38	.007	.014	.06	.03	.015	.051
	LCC	WQT	.18	1.11	.36	.02	.02	—	—	—	—
	LC1	NQT	.17	.78	.40	.02	.008	.06	.11	.53	.09
	LC2	NQT	.12	.63	.41	.011	.013	.05	2.6	.01	.016
	LC2-1	NQTA	.08	.58	.35	.012	.010	1.40	3.00	.52	.047
	LC3	WQT	.12	.82	.36	.01	.013	.18	3.9	.06	.009
757	C1Q	NQTA	.18	.89	.34	.01	.006	.03	1.72	.22	.034
	C1Q	ANQT	.21	.87	.39	.014	.014	.06	1.67	.28	.041
	E1Q	NQT	.07	.61	.30	.022	.003	1.42	2.87	.39	.017
	E1Q	ANQT	.10	.75	.34	.018	.013	1.83	2.90	.42	.054
	E3N	NT	.05	.51	.57	.025	.009	12.4	3.25	.63	.03

[A] See Table 9 for tensile and low temperature toughness properties.

[B] NT = Normalized and Tempered.

WQT = Water Quenched and Tempered.

WQTSR = Water Quenched and Tempered and Stress Relieved.

NQTA = Normalized, Quenched, Tempered and Aged.

GENERAL ENGINEERING TYPES

CLASSIFIED ACCORDIN

STRUCTURAL GRADES—CARBON STEELS

Tensile Strength, psi	60,000	65,000	70,000	80,000	85,000	100,000
Indicated Application	Low electric resistivity, desirable magnetic properties, carburizing and case hardening grades, excellent weldability	Excellent weldability, medium strength with good machinability and high ductility		High strength carbon steels with good machinability, toughness and excellent fatigue resistance, readily weldable		Wear resistance, hardness

All values listed below are specification minimum values and apply only to the typical specification listed

Tensile Strength, psi	60,000	65,000	70,000	80,000	85,000	100,000
Yield Point, psi	30,000	35,000	36,000	40,000	45,000	70,000
Elongation in 2", %	24	24	22	17	16	10
Reduction in Area, %	35	35	30	25	24	15
Brinell Hardness No.	—	131[3]	—	163[3]	170[3]	207[3]

Values listed directly below are those normally expected in the production of steel castings for the tensile strength values given in the upper portion of the chart.[4] The values are only for general information and are not to be used as design or specification limit values.

Tensile Strength, psi		63,000	68,000	75,000	82,000	90,000	105,000
Yield Point, psi		35,000	38,000	42,000	48,000	55,000	75,000
Elongation in 2", %		30	28	27	23	20	19
Reduction of Area, %		54	48	45	40	38	41
Brinell Hardness No.		131	131	143	163	179	212
Charpy V-Notched Impact Ft-lbs	70°F	12	35	30	35	26	40
	−40°F	5	12	12	10	10	12
Endurance Limit, psi	Unnotched	30,000	30,000	35,000	37,000	39,000	45,000
	Notched	19,000	19,000	22,000	26,000	28,000	31,000
Modulus of Elasticity		30 million psi	30 million psi	30 million psi	30 million psi	30 million psi	30 million psi
Machinability Speed Index[5]	HSS	160	135	135	135	120	80
	Carbide	400	230	230	400	325	310
Type of Heat Treatment		Annealed	Normalized	Normalized	Normalized and Tempered	Normalized and Tempered	Quenched and Tempered

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* Summary of Steel Castings Specifications available from Steel Founders' Society of America.

[1] Below 8 percent total alloy content.

[2] There are commercial cast steels available at tensile strength levels greater than 200,000 psi. Properties must be checked with the producers.

[3] SAE Hardness requirement. (Minimum)

OF CAST STEEL GRADES

TENSILE STRENGTHS

ENGINEERING GRADES—LOW ALLOY STEELS[1]

65,000	70,000	80,000	90,000	105,000	120,000	150,000	175,000	200,000[2]
Excellent weldability, low temperature and high temperature service	Excellent weldability, medium strength with high toughness and good machinability, high temperature service		Certain steels of these classes have excellent high temperature properties and deep hardening properties. High resistance to impact, excellent low temperature properties for certain steels, deep hardening properties, excellent combination of strength and toughness, weldable			Deep hardening, high strength, wear resistance and fatigue resistance	High strength, wear resistance, high hardness, and high fatigue resistance	
ASTM: A352 Class LC1	ASTM: A217 Class WC4	ASTM: A148 Class 80-50	ASTM: A148 Class 90-60	ASTM: A148 Class 105-85	ASTM: A148 Class 120-95	ASTM: A148 Class 150-125	ASTM: A148 Class 175-145	None specified

All values listed below are specification minimum values and apply only to the typical specification listed

65,000	70,000	80,000	90,000	105,000	120,000	150,000	175,000	—
35,000	40,000	50,000	60,000	85,000	95,000	125,000	145,000	—
24	20	22	20	17	14	9	6	—
35	35	35	40	35	30	22	12	—
—	—	163[3]	187[3]	217[3]	248[3]	311[3]	363[3]	—

Values listed directly below are those normally expected in the production of steel castings for the tensile strength values given in the upper portion of the chart.[4] The values are only for general information and are not to be used as design or specification limit values.

68,000	74,000	86,000	95,000	110,000	128,000	158,000	179,000	205,000
38,000	44,000	54,000	64,000	91,000	112,000	142,000	160,000	170,000
32	28	24	20	21	16	13	11	8
55	50	46	44	48	38	30	25	21
137	143	170	192	217	262	311	352	401
60	55	48	40	58	45	30	24	14
20	22	18	16	40	31	17	12	8
32,000	35,000	39,000	42,000	53,000	62,000	74,000	84,000	88,000
20,000	23,000	25,000	31,000	34,000	37,000	44,000	48,000	50,000
30 million psi	30 million psi	30 million psi	30 million psi	30 million psi	30 million psi	30 million psi	30 million psi	30 million psi
130	120	110	95	90	75	45	35	—
400	230	240	290	310	180	200	180	—
Normalized and Tempered	Normalized and Tempered	Normalized and Tempered	Normalized[6] and Tempered	Quenched and Tempered	Quenched and Tempered	Quenched and Tempered	Quenched and Tempered	Quenched and Tempered

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4 Test values obtained in accordance with ASTM testing procedures. (Relatively large castings show lower ductility values.)

5 Machinability speed index for a standard 18-4-1 high-speed steel tool is based on cutting speed which gives one hour tool life. For carbide (78B) cutting speed for one hour tool life based on 0.015-inch wearland.

6 Quench and temper heat treatments may also be employed for this class.

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