STEEL CASTINGS HANDBOOK

SUPPLEMENT 11

HARDENABILITY AND HEAT TREATMENT

STEEL FOUNDERS'
SOCIETY OF AMERICA

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Steel Castings Handbook
Supplement 11

Hardenability and Heat Treatment

Preface

This supplement describes the concept of hardenability and gives a method of determining the hardenability of cast steel from the chemical composition of the steel. In addition, the metallurgical features of various heat treatment cycles are reviewed. This information can be used as an aid in selecting the proper cast steel alloy and the heat treatment required to produce the desired final mechanical properties and microstructure.

Chapter references in this supplement refer to chapters in the Steel Castings Handbook, 5th Edition, published by the Steel Founders' Society of America.

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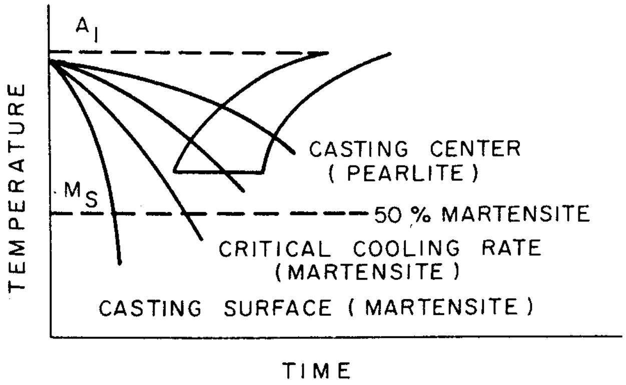

Fig. 1 The difference in the cooling rates at the surface and center of a steel casting and the resulting microstructures obtained.

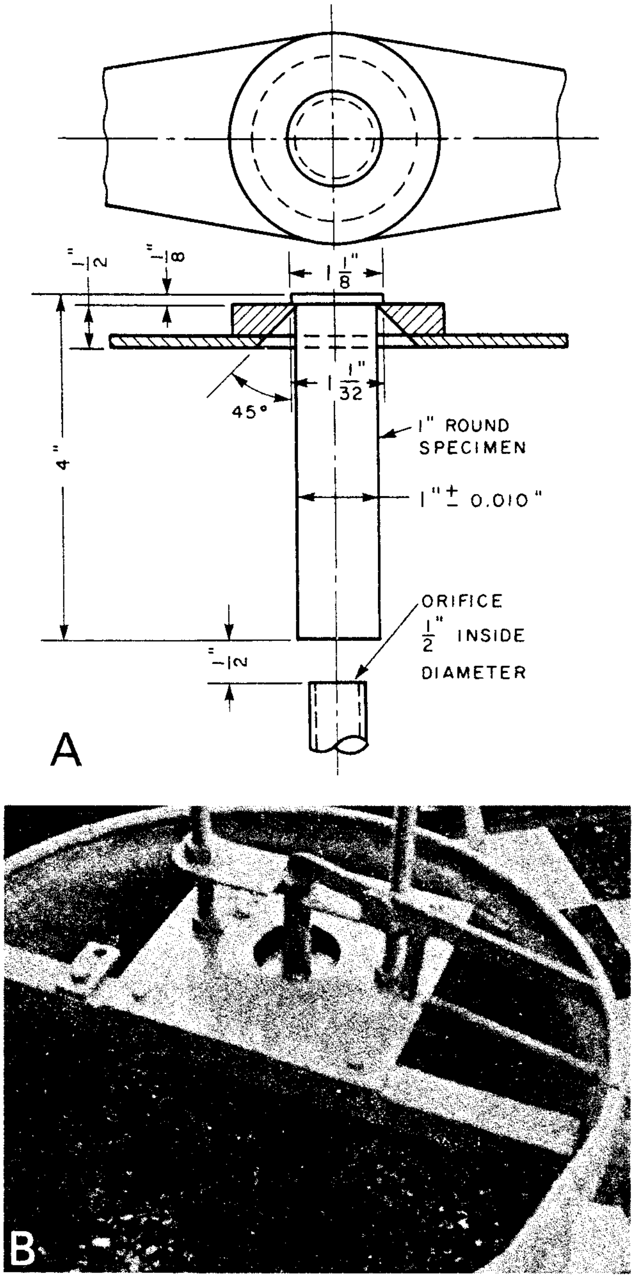

Fig. 2 A. Jominy test specimen and support for water quench and determination of hardenability (1 in. = 25.4 mm).
B. Performing the end quench test.

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Hardenability is the property of steel that governs the depth to which hardening occurs in a section during quenching. It should not be confused with hardness, which is the resistance to penetration as measured by the Rockwell, Brinell, or other hardness tests. Hardenability is of considerable importance because it relates directly to the strength of steel, as well as to many other mechanical properties, notably toughness and fatigue properties.

The principal method of hardening carbon and low alloy steels consists of quenching the steel from the austenitizing temperature. Steels vary in their response to this quenching operation because the depth below the surface of a part to which the part hardens will depend on the composition of the steel and the severity of the quench. Since the cooling rate during a quench is fastest at the surface of a part and slowest at its center, and since the hardening reaction is time dependent, the composition of a steel, i.e. its hardenability, is a vital consideration in alloy selection. This can be explained by reference to Figure 1, which shows schematically the cooling curves for the center and surface of a hypothetical steel section superimposed on the continuous cooling transformation diagram. The curve marked "50% martensite" intersects briefly the pearlite area; thus, half of the mass is transformed to pearlite and half transforms later to martensite. At some point closer to the surface, the cooling rate is given by the curve marked "critical cooling rate." This curve represents the cooling rate that is just fast enough to avoid transformation to any type of metallurgical structure except martensite.

Other steels, depending on their composition, may have the transformation area of Figure 1 shifted to the right (longer time). While the cooling curves for the surface and center would remain the same, the curve for 50% martensite would represent a slower cooling rate and might approximate the cooling rate at the center of the section. The critical cooling rate would also be slower, and the result might be that the second steel quenched to 50% or more martensite at the center.

Hardenability is a function of austenite grain size and composition of the steel. The grain size of importance is that which exists when the steel goes into the quench. For most *cast* steels, this grain size is small and does not vary widely. Hardenability of cast steels, therefore, is determined largely by the steel's analysis.

End Quench Test

The end quench test is used to measure the hardenability of a steel. In this test, a 1-in. diameter, 4-in. long cylinder (25.4 mm, and 101.6 mm) is heated to the austenitizing temperature appropriate to the steel. This temperature may be as low as 1500°F (816°C) or as high as 1700°F (927°C), but most steels will be heated in the range of 1600 to 1650°F (871–899°C). Special precautions are taken to minimize scaling during heating.

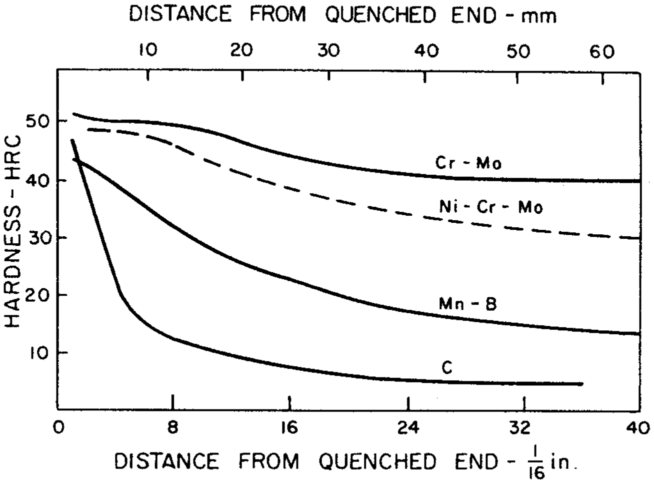


Fig. 3 Hardenability curves for C, Mn-B, Ni-Cr-Mo, and Cr-Mo cast steels.

The sample is quickly transferred from the furnace to a jig where it is suspended vertically over a 1/2-in. (12.7 mm) nozzle. Figure 2 shows the details of the test set-up and a photograph of the test being performed.

At the lower end, the sample is subjected to a continuous stream of water from the nozzle. At this end, the sample is subjected to conditions equivalent to violent water quenching and at the upper end the cooling rate approximates air cooling. Rates comparable to still water quenching, oil quenching and forced air cooling are represented at points between the lower and upper ends of the sample.

After the specimen has cooled completely, it is removed from the test fixture and two flat faces, 180 degrees apart, are ground along the length of the sample. Rockwell C hardness readings are taken on the flat faces from the quenched end in increments of 1/16 in. (1.59 mm). The hardness readings are plotted against distance from the quenched end to produce the hardenability or end quench curve. Figure 3 shows the end quench curves for four steels to show the various shapes assumed by these curves. The carbon steel is shallow hardening and the chromium-molybdenum type is fairly deep hardening.

Analyses of heats of a given grade of steel vary within limits. Therefore, the end quench curves vary slightly from heat to heat. When enough heats have been tested, their end quench curves will form a band. A number of end quench bands are shown later in this chapter (Figures 12 to 30).

Calculated End Quench Curves

There are cases where end quench curves are not available, such as in alloy development, or where the end quench test is not practical, such as determining whether or not a heat will meet a hardenability specification. In these cases, the end quench curve is computed from analysis.

The first step in the computation is calculation of the ideal critical diameter (D_I). This is the diameter of the largest cylinder which will have 50% martensite at the center when the cylinder has been cooled in an ideal quench. The ideal quench is one in which the surface of the workpiece drops instantly to the quenchant temperature and is maintained at that temperature. The calculation of ideal critical diameter was originally developed by Grossman and has remained essentially unchanged (**1**).

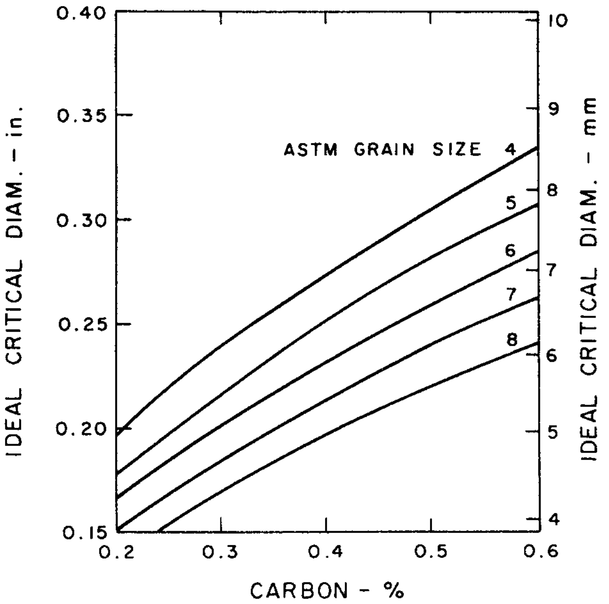


Fig. 4 The effect of ASTM grain size and carbon content on the ideal critical diameter D_I(**2**).

Figure 4 gives the ideal diameter as a function of the carbon content for various austenite grain sizes. For cast steels, the curve for grain size 8 is ordinarily used. Having established the diameter (D_{IC}) for the steel's carbon content, the next step is to refer to Figure 5 for the multiplying factors (*MF*) of the alloying elements. The ideal critical diameter is calculated from the formula:

$$D_I = D_{IC}(MF_{Mn})(MF_{Si})(MF_{Ni}) \ldots \text{etc.}$$

In applying the formula, residual elements as well as alloying elements must be included. The factor for copper is the same as that for nickel.

The calculation as outlined does not provide for including the effect of vanadium or boron. There is some uncertainty about the behavior of these elements. Vanadium up to about 0.1% increases hardenability, but beyond that there is considerable doubt about its effect. Further increases may even decrease hardenability. The reason for this apparent discrepancy lies in the fact that hardenability is determined by the composition of austenite at the austenitizing temperature, rather than by the overall composition of steel. Vanadium-rich carbides form at higher vanadium levels and are difficult to dissolve at standard austenitizing temperatures.

Boron increases hardenability of steels with carbon contents below about 0.3% and has little or no effect

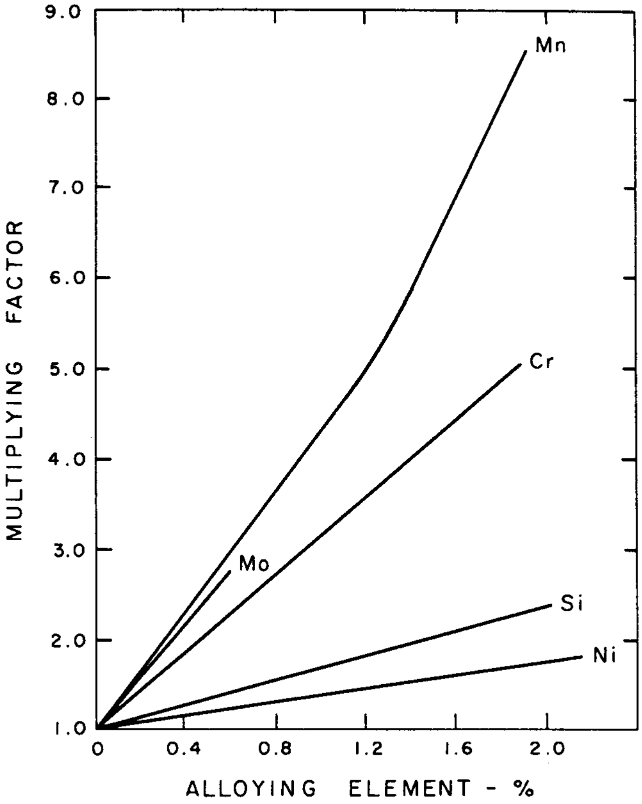


Fig. 5 The effect of alloying elements on the hardenability index D_I for cast steel (**2**).

in higher carbon steels. Boron is not widely used because it is difficult to achieve consistent hardenability from boron alloyed steels. When boron does raise hardenability, it seems to have more effect when added to a shallow-hardening steel than it has in a steel with higher hardenability. When dealing with these two elements, it is best to make a few heats with and without vanadium or boron to get some idea of the effect on the base alloy.

Since most cast steels contain neither vanadium nor boron, the calculation as outlined above is of considerable value.

Calculation of D_I using graphs can be tedious and error prone. There have been slide-rule type calculators produced for computing D_I . Table 1 (3) can be used to determine the value of D_I . This is accomplished by summing the appropriate numbers from Table 1. This sum is then used to determine the value of D_I from Table 2. Cast steels, because of aluminum deoxidation have a grain size of 8, and hence only one carbon factor is needed.

TABLE 2

Conversion of D_I Factor (Sum from Table 1) to D_I (Inches)

Sum	D_I	Sum	D_I	Sum	D_I	Sum	D_I
1.00	1.00	1.22	1.66	1.44	2.75	1.66	4.57
1.01	1.02	1.23	1.70	1.45	2.82	1.67	4.68
1.02	1.05	1.24	1.74	1.46	2.88	1.68	4.79
1.03	1.07	1.25	1.78	1.47	2.95	1.69	4.90
1.04	1.10	1.26	1.82	1.48	3.02	1.70	5.01
1.05	1.12	1.27	1.86	1.49	3.09	1.71	5.13
1.06	1.15	1.28	1.90	1.50	3.16	1.72	5.25
1.07	1.18	1.29	1.95	1.51	3.24	1.73	5.37
1.08	1.20	1.30	2.00	1.52	3.31	1.74	5.50
1.09	1.23	1.31	2.04	1.53	3.39	1.75	5.62
1.10	1.26	1.32	2.09	1.54	3.47	1.76	5.75
1.11	1.29	1.33	2.14	1.55	3.55	1.77	5.89
1.12	1.32	1.34	2.19	1.56	3.63	1.78	6.03
1.13	1.35	1.35	2.24	1.57	3.72	1.79	6.17
1.14	1.38	1.36	2.29	1.58	3.80	1.80	6.31
1.15	1.41	1.37	2.34	1.59	3.89	1.81	6.46
1.16	1.44	1.38	2.40	1.60	3.98	1.82	6.61
1.17	1.48	1.39	2.46	1.61	4.07	1.83	6.76
1.18	1.51	1.40	2.51	1.62	4.17	1.84	6.92
1.19	1.55	1.41	2.57	1.63	4.27	1.85	7.08
1.20	1.59	1.42	2.63	1.64	4.37	1.86	7.24
1.21	1.62	1.43	2.69	1.65	4.47	1.87	7.41

TABLE 1

Used for Calculation of D_I Factor (Sum)

% Element	Carbon	Manganese	Silicon	Chromium	Nickel & Copper	Molybdenum
0.20	.1458	.2227	.0569	.1556	.0306	.2041
0.25	.1929	.2636	.0700	.1875	.0378	.2430
0.30	.2317	.3010	.0828	.2170	.0453	.2788
0.35	.2658	.3306	.0952	.2445	.0523	.3118
0.40	.2967	.3677	.1072	.2705	.0592	.3424
0.45	.3222	.3976	.1189	.2949	.0663	.3711
0.50	.3444	.4255	.1303	.3181	.0730	.3979
0.55	.3614	.4518	.1415	.3403	.0795	
0.60	.3838	.4767	.1523	.3610	.0860	
0.65		.5001	.1629	.3811	.0924	
0.70		.5226	.1732	.4000	.0986	
0.75		.5437	.1833	.4185	.1052	
0.80		.5640	.1931	.4358	.1109	
0.85		.5831	.2028	.4528	.1169	
0.90		.6017	.2122	.4689	.1229	
0.95		.6192	.2214	.4847	.1284	
1.00		.6368	.2305	.4997	.1339	
1.05		.6531	.2393	.5142	.1399	
1.10		.6688	.2480	.5284	.1461	
1.15		.6840	.2565	.5422	.1517	
1.20		.6986	.2648	.5553	.1569	
1.25		.7199	.2730	.5683	.1626	
1.30		.7401	.2810	.5807	.1679	
1.35		.7593	.2889	.5930	.1735	
1.40		.7779	.2967	.6047	.1790	
1.45		.7961	.3043	.6163	.1847	
1.50		.8137	.3118	.6274	.1901	
1.55		.8304	.3191	.6384	.1967	
1.60		.8464	.3263	.6490	.2030	
1.65		.8625		.6594	.2093	
1.70		.8777		.6695	.2151	
1.75		.8923		.6795	.2217	
1.80		.9064		.6891	.2279	
1.85		.9199		.6987	.2335	
1.90		.9303		.7079	.2430	
1.95		.9440		.7171	.2453	
2.00		.9584		.7259	.2499	
2.05					.2560	
2.10					.2620	
2.15					.2686	
2.20					.2751	
2.25					.2817	
2.30					.2880	
2.35					.2956	
2.40					.3030	
2.45					.3107	
2.50					.3181	

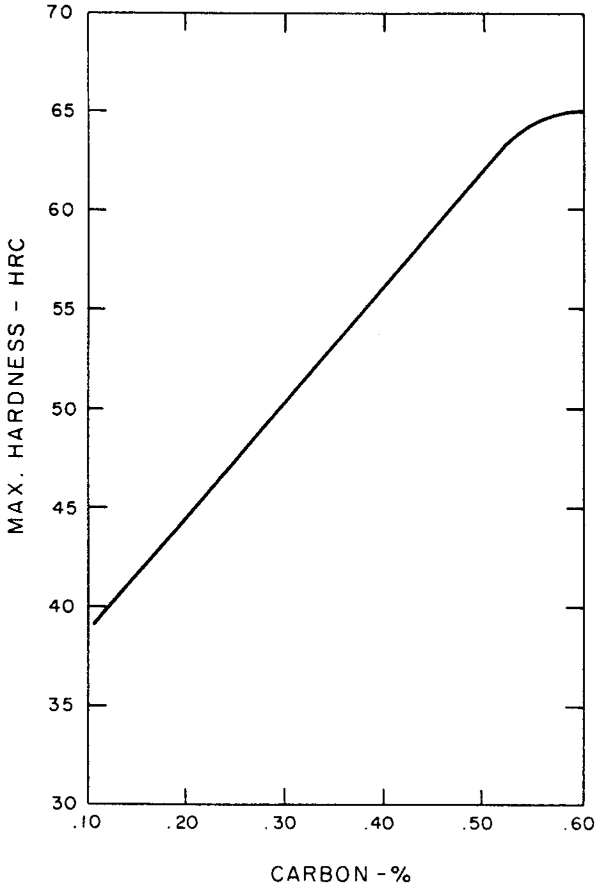


Fig. 6 The maximum hardness at the quenched end as a function of carbon content (**2**).

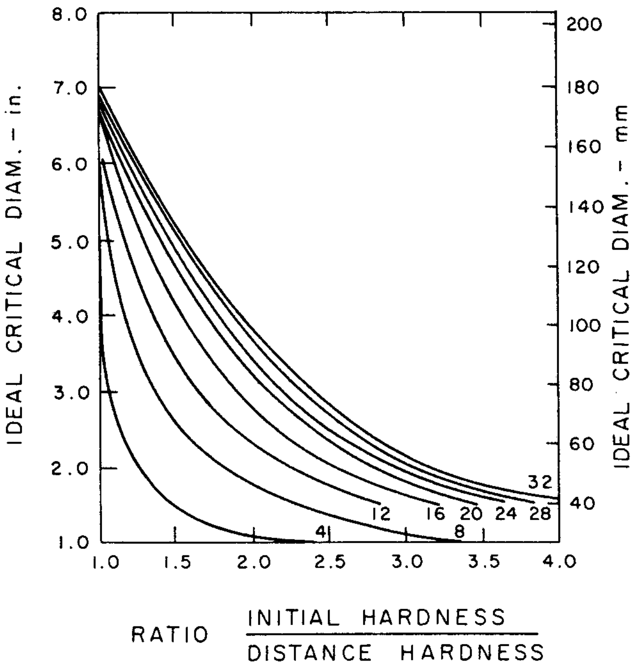


Fig. 7 Curves used for the determination of hardness for certain distances from the quenched end (**2**).

Once D_I has been determined, the end-quench curve can be established from Figures 6 and 7. Figure 21-6 gives the maximum hardness as a function of carbon content. This is the initial hardness that is plotted 1/16 in. (1.59 mm) from the quenched end. It is also used in the ratio of initial hardness to distance hardness in Figure 7. The numbers on the curves of Figure 7 indicate the number of 1/16-in. (1.59 mm) increments from the quenched end. For example, 4/16, 8/16, 12/16 in. (6.35, 12.70, 19.05 mm), etc. Using the D_I determined earlier, proceed horizontally across the graph and note the ratio called out by the intersection with each curve. The hardness at the indicated distances from the quenched end can then be caluclated and plotted to draw the end-quench curve.

The end quench curve can also be drawn by use of Table 3 (4) which gives the hardness values at various distances from the quenched end for various combinations of D_I and carbon content.

It is possible to construct the end-quench band for a given alloy by drawing a curve for the maximum D_I and another for the minimum D_I. Computing D_I for a heat with all the elements at the top of the specification range and another with all the elements at their lower limits would result in a band which is absurdly wide. Since these extreme conditions do not occur, the problem becomes one of probability mathematics. The problem is avoided by calculating D_I for 50 to 100 heats and, by statistical analysis, determining the distribution of D_I and thus the maximum and minimum values.

Table 4 shows calculated D_I values for various steels that are covered by the ASTM Specification A487. The compositions used for computing D_I are included in the table.

Application of Ideal Critical Diameter D_I

The definition of D_I assumes that the work is cooled in an ideal quench. Real quenching operations can only approach these ideal conditions. The depth of hardening obtained in practice therefore depends not only on the steel's hardenability but also the rate of cooling or severity of quench.

Severity of quench is expressed by a number which is designated as "H value"; the larger the H value, the more severe the quench. The H value depends mainly on the quenching medium, its temperature, and the degree of agitation during quenching. Table 5 lists H values for quenching conditions often found in the foundry.

The diameter of a cylinder which will quench to 50% martensite at the center (D) in commercial

TABLE 3-1

0.20% Carbon

D_I	Jominy Distance (1/16 in.)								
(in.)	1	4	8	12	16	20	24	28	32
1.50	44.5	30.0	19.3	15.7	13.9	12.7	12.0	11.5	10.2
2.00	44.5	36.0	25.2	20.1	17.5	16.2	15.5	15.0	14.5
2.50	44.5	39.1	29.0	24.0	20.8	18.7	18.0	17.4	16.9
3.00	44.5	41.4	32.0	26.8	23.5	21.2	20.1	19.3	18.9
3.50	44.5	42.4	34.5	29.5	25.6	23.4	22.3	21.5	21.0
4.00	44.5	43.0	37.0	31.9	28.2	25.8	24.7	23.8	23.2
4.50	44.5	43.9	39.1	35.0	31.0	28.8	27.5	26.6	25.7
5.00	44.5	44.5	41.0	38.0	34.2	32.0	30.6	29.4	28.5
5.50	44.5	44.5	43.0	40.9	37.4	35.0	34.0	32.9	32.0
6.00	44.5	44.5	44.0	42.6	40.5	39.0	38.0	37.1	36.2
6.50	44.5	44.5	44.5	44.2	43.3	42.5	41.7	41.2	40.4
7.00	44.5	44.5	44.5	44.5	44.5	44.5	44.5	44.1	43.6

TABLE 3-2

0.25% Carbon

D_I	Jominy Distance (1/16 in.)								
(in.)	1	4	8	12	16	20	24	28	32
1.50	47.5	32.0	20.5	16.8	14.9	13.8	13.1	12.3	11.7
2.00	47.5	38.3	27.0	21.5	18.8	17.3	16.5	16.0	15.5
2.50	47.5	42.0	31.1	25.6	22.2	20.1	19.3	18.5	18.0
3.00	47.5	44.1	34.2	28.5	25.0	22.6	21.5	20.7	20.2
3.50	47.5	45.4	37.0	31.5	27.5	25.0	24.0	23.0	22.5
4.00	47.5	45.8	39.4	34.0	30.1	27.5	26.4	25.4	24.9
4.50	47.5	46.6	41.8	37.2	33.1	30.7	29.3	28.3	27.4
5.00	47.5	47.5	44.0	40.5	36.5	34.0	32.7	31.3	30.6
5.50	47.5	47.5	45.6	43.4	39.9	37.5	36.1	35.0	34.1
6.00	47.5	47.5	47.0	45.4	43.0	41.3	40.2	39.2	38.5
6.50	47.5	47.5	47.5	47.0	46.0	45.1	44.0	43.5	43.0
7.00	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.0	46.6

TABLE 3-3

0.30% Carbon

D_I	Jominy Distance (1/16 in.)								
(in.)	1	4	8	12	16	20	24	28	32
1.50	50.0	33.9	20.6	17.7	15.7	14.5	13.8	13.2	12.4
2.00	50.0	40.4	28.3	22.5	19.7	18.1	17.4	16.8	16.2
2.50	50.0	45.0	33.1	27.5	23.5	21.4	20.5	19.7	19.2
3.00	50.0	47.0	36.5	30.5	26.7	24.0	23.0	22.0	21.5
3.50	50.0	48.0	39.3	33.4	29.0	26.6	25.4	24.5	24.0
4.00	50.0	49.0	42.0	36.4	32.3	29.5	28.3	27.2	26.5
4.50	50.0	49.5	44.4	40.0	35.5	32.8	31.1	30.0	29.0
5.00	50.0	50.0	46.5	43.0	38.7	36.1	34.6	33.1	32.2
5.50	50.0	50.0	48.5	46.1	42.0	39.6	38.3	37.1	36.2
6.00	50.0	50.0	49.5	48.0	45.5	43.5	42.4	41.5	40.7
6.50	50.0	50.0	50.0	49.6	48.4	47.8	46.7	46.1	45.2
7.00	50.0	50.0	50.0	50.0	50.0	50.0	50.0	49.4	49.0

TABLE 3-4

0.35% Carbon

D_I (in.)	Jominy Distance (1/16 in.)								
	1	4	8	12	16	20	24	28	32
1.50	53.0	36.0	23.3	18.9	16.8	15.5	14.7	14.0	13.5
2.00	53.0	42.8	30.0	24.0	21.0	19.3	18.5	17.9	17.3
2.50	53.0	47.0	35.0	28.7	24.9	22.5	21.5	20.8	20.2
3.00	53.0	49.5	38.2	32.1	28.0	25.3	24.1	23.2	22.7
3.50	53.0	51.0	41.4	35.1	31.0	28.2	26.8	25.7	25.2
4.00	53.0	51.5	44.0	38.0	33.9	31.0	29.6	28.5	27.9
4.50	53.0	52.1	45.8	42.0	37.1	34.5	33.0	31.7	30.8
5.00	53.0	53.0	49.1	45.2	40.8	38.0	36.5	35.0	34.1
5.50	53.0	53.0	51.0	48.5	44.6	42.0	40.5	39.2	38.1
6.00	53.0	53.0	52.2	50.9	47.0	46.3	45.0	44.0	43.0
6.50	53.0	53.0	53.0	52.5	51.4	50.5	49.4	49.0	48.0
7.00	53.0	53.0	53.0	53.0	53.0	53.0	53.0	52.5	52.0

TABLE 3-5

0.40% Carbon

D_I (in.)	Jominy Distance (1/16 in.)								
	1	4	8	12	16	20	24	28	32
1.50	56.0	37.6	24.3	19.8	17.5	16.3	15.4	14.6	14.0
2.00	56.0	45.0	31.7	25.2	22.0	20.4	19.5	18.6	18.0
2.50	56.0	49.5	36.7	30.3	26.0	23.5	22.5	21.9	21.3
3.00	56.0	52.0	40.1	33.8	29.5	26.5	25.4	24.4	23.9
3.50	56.0	53.5	44.6	37.0	32.5	29.5	28.0	27.0	26.5
4.00	56.0	54.2	46.6	40.2	35.6	32.5	31.1	30.0	29.5
4.50	56.0	55.0	49.0	44.0	39.0	36.1	34.5	33.3	32.3
5.00	56.0	56.0	52.0	48.0	43.1	40.2	38.7	37.0	36.0
5.50	56.0	56.0	54.0	51.4	47.0	44.1	42.9	41.4	40.2
6.00	56.0	56.0	55.5	53.6	50.9	48.8	47.5	46.6	45.5
6.50	56.0	56.0	56.0	55.5	54.0	53.1	52.0	51.5	50.6
7.00	56.0	56.0	56.0	56.0	56.0	56.0	56.0	55.6	55.0

TABLE 3-6

0.45% Carbon

D_I (in.)	Jominy Distance (1/16 in.)								
	1	4	8	12	16	20	24	28	32
1.50	59.0	39.6	25.5	20.8	18.5	17.1	16.2	15.4	14.8
2.00	59.0	47.5	33.3	26.5	23.2	21.4	20.5	19.6	19.0
2.50	59.0	52.0	38.5	32.0	27.5	24.9	23.7	23.0	22.4
3.00	59.0	54.5	42.3	35.5	31.0	28.0	26.7	25.5	25.0
3.50	59.0	56.0	45.8	38.9	34.0	31.0	29.5	28.4	27.8
4.00	59.0	57.0	49.0	42.1	37.5	34.2	32.9	31.6	31.0
4.50	59.0	58.0	52.0	46.5	41.1	38.0	36.5	35.0	34.0
5.00	59.0	59.0	54.5	50.0	45.2	43.2	40.5	39.0	37.9
5.50	59.0	59.0	56.9	54.0	49.5	46.5	45.0	43.5	42.3
6.00	59.0	59.0	58.0	56.1	53.5	51.4	50.0	49.0	48.0
6.50	59.0	59.0	59.0	58.0	57.0	56.1	55.0	54.4	53.3
7.00	59.0	59.0	59.0	59.0	59.0	59.0	59.0	58.2	57.9

TABLE 3-7

0.50% Carbon

D_I (in.)	Jominy Distance (1/16 in.)								
	1	4	8	12	16	20	24	28	32
1.50	62.0	41.6	27.0	22.0	19.5	18.0	17.1	16.4	15.6
2.00	62.0	50.0	35.0	28.0	24.5	22.5	21.5	20.7	20.1
2.50	62.0	55.0	40.8	33.5	29.0	26.1	25.0	24.2	23.5
3.00	62.0	57.6	44.5	37.4	32.8	29.5	28.1	27.0	26.5
3.50	62.0	59.4	48.3	41.1	36.0	32.9	31.1	30.0	29.4
4.00	62.0	60.0	51.4	44.5	39.3	36.0	34.5	33.1	32.5
4.50	62.0	60.9	54.5	48.7	43.3	40.0	38.0	36.8	35.6
5.00	62.0	62.0	57.4	52.8	47.5	44.5	42.5	41.0	39.9
5.50	62.0	62.0	59.6	51.7	52.0	48.8	47.0	45.9	44.5
6.00	62.0	62.0	61.3	59.4	56.1	54.0	52.6	51.6	50.5
6.50	62.0	62.0	62.0	61.4	60.0	59.0	58.0	57.1	56.0
7.00	62.0	62.0	62.0	62.0	62.0	62.0	62.0	61.0	60.5

TABLE 3-8

0.55% Carbon

D_I (in.)	Jominy Distance (1/16 in.)								
	1	4	8	12	16	20	24	28	32
1.50	64.5	43.5	27.8	22.7	20.3	18.6	17.8	17.0	16.2
2.00	64.5	52.0	35.5	29.0	25.5	23.4	22.5	21.6	21.0
2.50	64.5	57.0	42.1	35.0	30.0	27.2	26.0	25.3	24.5
3.00	64.5	60.0	46.4	38.8	34.0	30.8	29.1	28.0	27.5
3.50	64.5	61.5	50.0	42.5	37.1	34.0	32.5	31.0	30.5
4.00	64.5	62.0	53.5	46.2	41.0	37.4	35.9	34.5	33.8
4.50	64.5	63.1	56.5	50.5	45.0	41.5	39.8	38.0	37.0
5.00	64.5	64.5	59.6	54.9	49.1	46.0	44.1	42.4	41.2
5.50	64.5	64.5	62.0	59.0	53.9	50.8	49.0	47.5	46.4
6.00	64.5	64.5	64.0	61.8	58.1	56.0	54.5	53.4	52.0
6.50	64.5	64.5	64.5	64.0	62.4	61.0	60.0	59.5	58.4
7.00	64.5	64.5	64.5	64.5	64.5	64.5	64.5	63.0	62.8

TABLE 3-9

0.60% Carbon

D_I (in.)	Jominy Distance (1/16 in.)								
	1	4	8	12	16	20	24	28	32
1.50	65.0	44.0	28.4	23.2	20.5	19.0	18.0	17.3	16.5
2.00	65.0	53.0	37.0	29.5	25.9	23.7	22.9	22.0	21.3
2.50	65.0	58.0	43.0	35.5	30.8	27.6	26.5	25.5	25.0
3.00	65.0	61.0	47.0	39.5	34.6	31.0	29.6	28.5	28.0
3.50	65.0	62.5	51.0	43.5	38.0	34.5	32.0	31.5	31.0
4.00	65.0	63.1	54.4	47.0	41.6	38.0	36.5	35.0	34.2
4.50	65.0	64.1	57.5	51.5	45.9	42.0	40.0	38.9	37.6
5.00	65.0	65.0	60.5	55.6	50.0	46.7	44.9	43.0	41.8
5.50	65.0	65.0	62.8	59.9	55.0	51.5	49.8	48.0	47.0
6.00	65.0	65.0	64.5	62.5	59.0	56.9	55.2	54.0	53.0
6.50	65.0	65.0	65.0	64.5	63.0	62.0	60.7	60.0	59.0
7.00	65.0	65.0	65.0	65.0	65.0	65.0	65.0	64.5	64.0

TABLE 4 Calculated D_I for ASTM A487 Low Alloy Steels

	Analysis[1] used in calculation—%								Calculated D_I	
Class	C	Mn	Si	Cr	Ni	Mo	Other		in.	mm
1N-1Q	.25	.80	.60	.15	.25	.10	V	.08	1.59(2)	40(2)
2N-2Q	.25	1.25	.60	.15	.25	.20			2.69	68
4N-4Q-4QA	.25	.80	.60	.60	.60	.23			3.86	98
6N-6Q	.33	1.50	.60	.60	.60	.35			9.48	241
7Q	.15	.80	.60	.60	.85	.50	V	.06	4.80(3)	122(3)
							Cu	.33		
							B	.004		
8N-8Q	.15	.70	.60	2.40	—	1.00			9.86	250
9N-9Q	.28	.80	.60	.90	.25	.23			4.63	118
10N-10Q	.25	.60	.60	.75	1.70	.30			5.42	138
11N-11Q	.15	.65	.40	.65	.90	.55			4.61	117
12N-12Q	.15	.55	.40	.70	.80	1.05			8.23	209
13N-13Q	.25	.95	.40	.20	1.60	.25			3.32	84
14Q	.50	.95	.40	.20	1.60	.25			4.70	119
A-AN-AQ	.20	.65	.40	.20	.25	.10			1.28	33
B-BN-BQ	.25	.90	.40	.20	.25	.10			1.62	41
C-CN-CQ	.20	1.10	.40	.20	.25	.10			1.70	43
DN	.45	.70	.40	.20	.25	.10			1.83	46

[1]Analysis used in calculation meets ASTM specification A487. [2]Does not include the effect of V. [3]Does not include the effect of V and B.

TABLE 5 Severity of Quench H-Values for Oil and Water

Agitation	H-Value	
	Oil	Water
None	.25-.30	1.00
Mild	.30-.35	1.00-1.10
Moderate	.35-.40	1.20-1.30
Good	.40-.50	1.40-1.50
Strong	.50-.80	1.60-2.00
Violent	.80-1.00	4.00

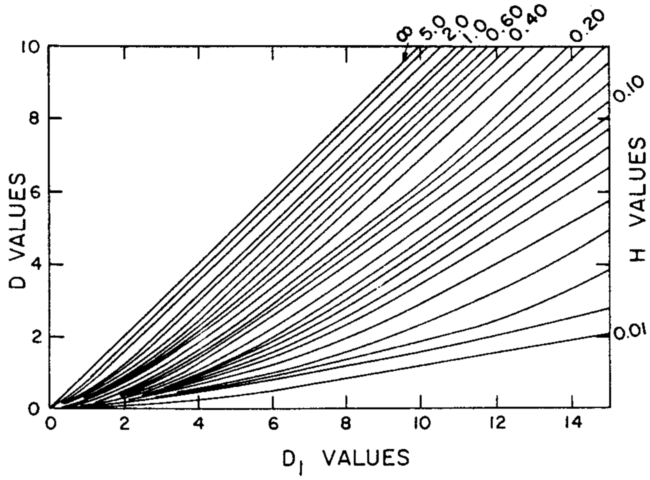


Fig. 8 Relationships among ideal critical size, D_I, actual critical size, D, and severity of quenching, H.

quenching operations will be less than the ideal critical diameter (D_I). Figure 8 shows the relation of D to D_I for quenches of various H values. For example, if a steel has $D_I = 4$ in. (101.6 mm) and is quenched in water where $H = 1.5$, a cylinder of 3.5 in. (88.9 mm) diameter will quench to 50% martensite at the

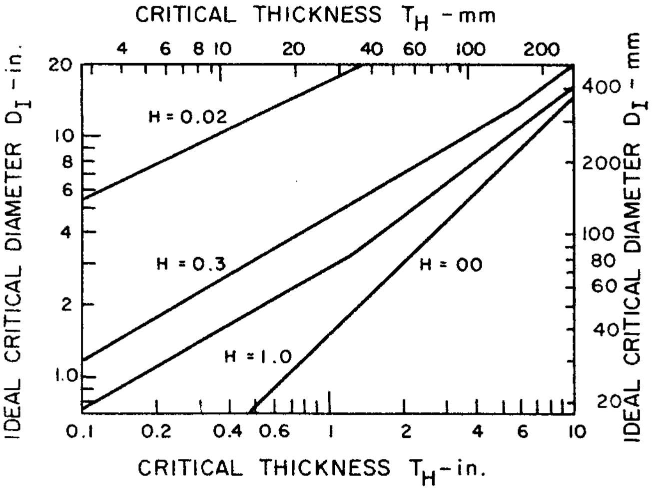


Fig. 9 The relation between ideal critical diameter, D_I , and the critical thickness, T_H that can be fully hardened using a quenching medium with severity H (5).

center. If a cylinder of the same steel is quenched in oil with $H = 0.4$, a cylinder of 2.25 in. (57.15 mm) diameter will harden to 50% martensite at the center.

The relationship of the ideal critical diameter and of the severity of quench to the thickness of plates is indicated in Figure 9. For example, assume that a plate of 4340 steel is quenched in still water. The parameters are:

$D_I = 6.42$ in. (163 mm)
$H = 1.00$ (from Table 21-2)

Figure 9 shows that the critical plate thickness is 3.0 in. (76.2 mm). This is the thickness of a plate which will harden to 50% martensite. In contrast, using the same parameters, a 6-in. (152.4 mm) diameter rod or cylinder will harden to 50% martensite in the center. The difference between plates and cylinders arises from the slower rate of cooling associated with plates.

Cooling Rate Equivalence

It was noted in connection with Figure 1 that different parts of a section cool at different rates. The rates are affected by the severity of quench as indicated in Figures 8 and 9. The cooling rates along the end-quench bar vary from very fast to very slow, depending on the distance from the quenched end. There should be a cooling rate at some point along the end-quench bar which corresponds to the cooling rate at a given point in the section for the conditions of section size and quench severity.

To determine this point on the end-quench bar the cooling rates of interest in the actual part are measured in the temperature interval of 1350°F (732°C) down to 600 or 700°F (316 or 371°C). This is the range where there is the greatest tendency of transformation to pearlite or bainite.

Figure 10 gives the end-quench equivalent at surface, center, and two intermediate points in cylindrical sections in quenches of different severities (7). The temperature ranges were from 1350 to 600°F (732 to 316°C) at the surface, to 700°F (371°C) at 3/4 radius, to 800°F (427°C) at 1/2 radius and 900°F (482°C) at the center. This distorts the relation with the end quench curve, but the greatest effect on the relation is due to the quenchant and agitation.

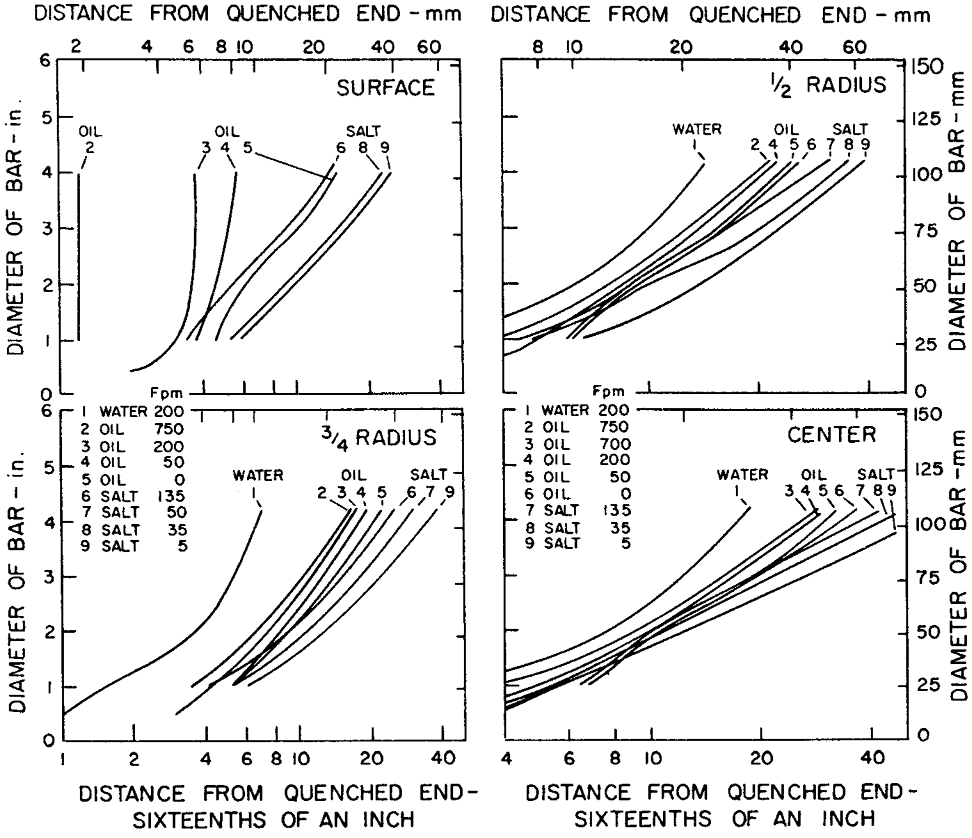


Fig. 10 Correlation curves for identical cooling times in end-quench hardenability specimens and round bars quenched in hot salt, oil, and water. Water was at 75° F (24° C); mineral oil [Saybolt universal viscosity at 100° F, (38° C), 79 sec], at 120° F (49° C); molten salt, at 400° F (204° C) (6).

TABLE 6 **Equivalent End Quench Distance Plates—Hardness at Center of Section**

Plate Thickness		Equivalent End Quench Distance Quenched in					
		Still Oil		Still Water		Agitated Water	
in.	mm	1/16 in.	mm	1/16 in.	mm	1/16 in.	mm
0.5	12.7	4.5	7.1	2.0	3.2	2.0	3.2
1.0	25.4	10.0	15.8	6.0	9.5	6.0	9.5
1.5	38.1	15.5	24.6	8.5	13.5	8.5	13.5
2.0	50.8	21.5	34.1	12.0	19.1	12.0	19.1
2.5	63.5	29.5	46.8	15.0	23.8	14.0	22.2
3.0	76.2			19.5	30.9	17.5	27.8
3.5	88.9			26.0	41.3	24.0	38.1

TABLE 7 **Equivalent End Quench Distance for Plates—Quenched in Agitated Water**

Plate Thickness		Equivalent End Quench Distance in 1/16 in. and mm (at three distances from the surface)					
in.	(mm)	1/16 in. (1.6 mm)		1/4 in. (6.4 mm)		Center	
0.5	(12.7)	1.3	(2.1)	2.0	(3.2)	2.0	(3.2)
1.0	(25.4)	2.0	(3.2)	4.0	(6.4)	6.0	(9.5)
1.5	(38.1)	2.5	(3.9)	6.0	(9.5)	8.5	(13.5)
2.0	(50.8)	2.5	(3.9)	8.0	(12.7)	12.0	(19.1)
2.5	(63.5)	3.0	(4.7)	10.0	(15.9)	14.0	(22.2)
3.0	(76.2)	3.0	(4.7)	12.5	(19.8)	17.5	(27.8)

The curves of Figure 10 may be used for bars of other cross sections such as square or hexagonal. The diameter is that of a circle inscribed in the section.

Data on end-quench equivalence of plates are not numerous. Table 6 gives the equivalent end-quench distance for the center of various plate thicknesses under different quenches. Table 4 shows the end-quench equivalent for different parts of plate sections quenched in agitated water.

Whether graphs such as Figure 10 or tables such as Table 7 are used, the result is equivalent distance from the quenched end for points in the cross section of the quenched piece. Reference must then be made to the end-quench curve for the alloy to find the Rockwell hardness traverse of the section. The use of this information will be discussed under Application of Hardenability Concepts.

Specifying Hardenability

Hardenability is specified in several different ways. The Society of Automotive Engineers Recommended Practice J-435a covers three grades of 0.3% carbon steel. The hardenability bands for the three grades are shown in Figure 11. The choice of analysis to fit the chosen grade is usually made by the manufacturer.

When the hardenability band is known for the steel, it can be accepted by both producer and customer and then the end-quench curve for each heat made to this specification will be required to fall within the band. In order to avoid the necessity of drawing a curve for each heat, the specification may simply call for a range of hardness at some stated distance from the quenched end. For example, it might call for Rockwell C 38 to 53 at 6/16 in. (9.5 mm) from the quenched end. The distance is generally chosen as the equivalent to a critical point in the section.

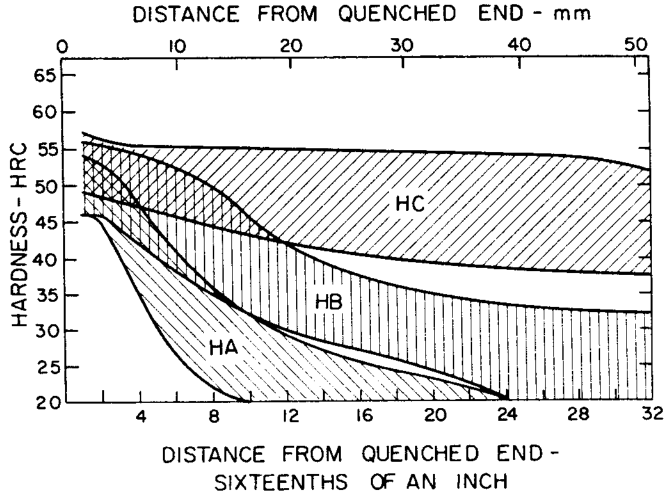


Fig. 11 Hardenability bands specified by SAE J-435a.

Another form of specification might call out the maximum and minimum distances from the quenched end for a given hardness. For example, Rockwell C 40 at 3/16 to 14/16 in. (4.7 – 22.2 mm) from the quenched end.

A common form of hardenability specification is the call for a range of the ideal critical diameter. As discussed above, this range is not calculated from the composition limits of the steel grade, but from the distribution of D_I values calculated from a number of production heats.

Hardenability Bands

Hardenability bands for cast steels have been determined by the Steel Founders' Society of America. They include carbon steels and many of the frequently used low alloy steels. The bands are shown in Figures 12 through 30.

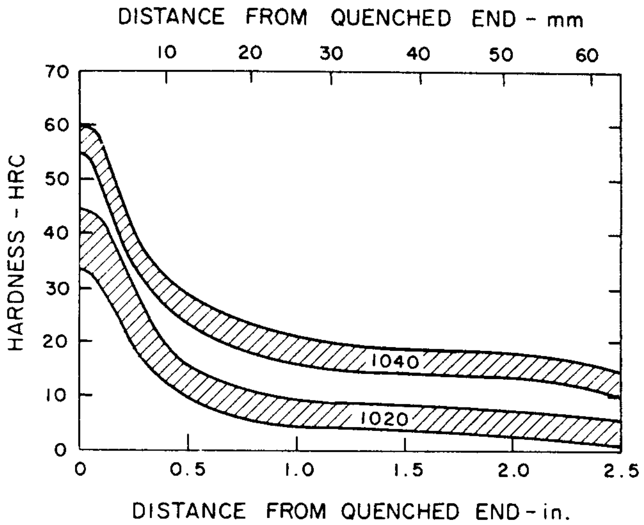


Fig. 12 Hardenability curves for carbon cast steels.

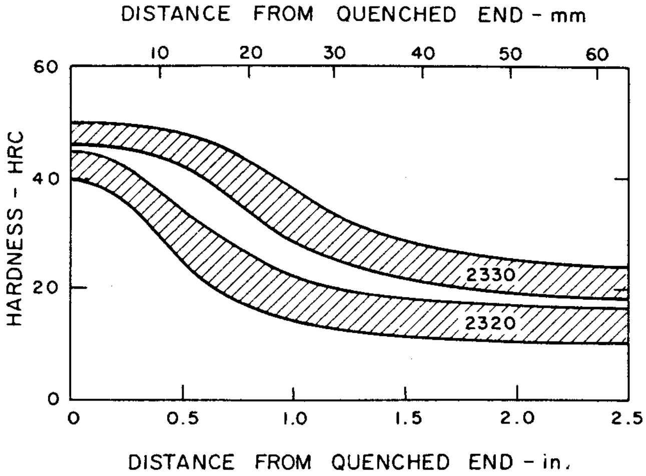


Fig. 15 End-quench hardenability of nickel (2320 and 2330) cast steel.

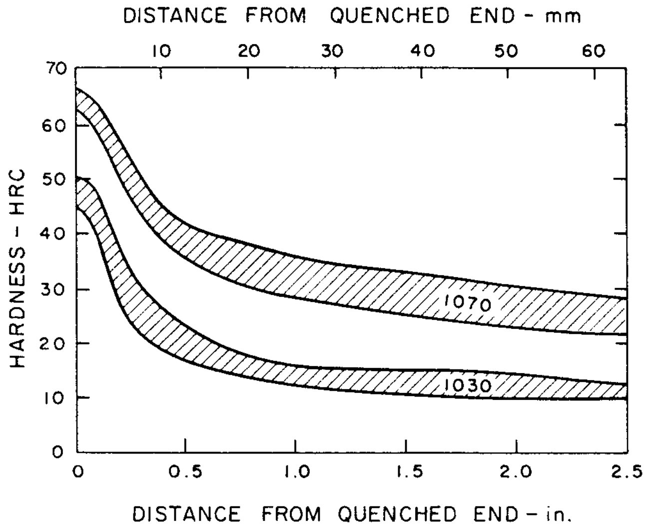


Fig. 13 Hardenability curves for carbon cast steels.

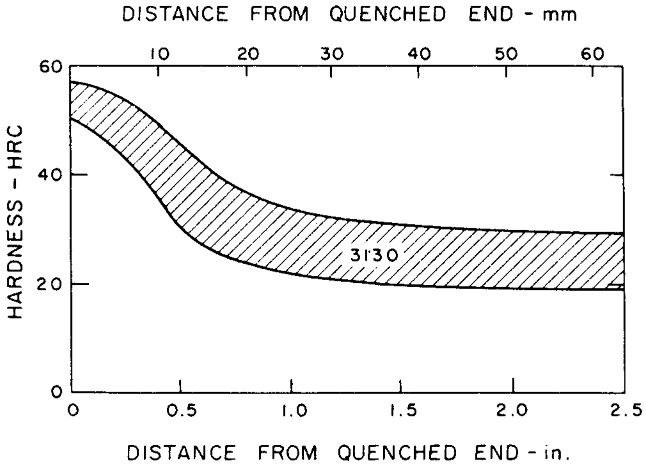


Fig. 16 End-quench hardenability of nickel-chromium (3130) cast steel.

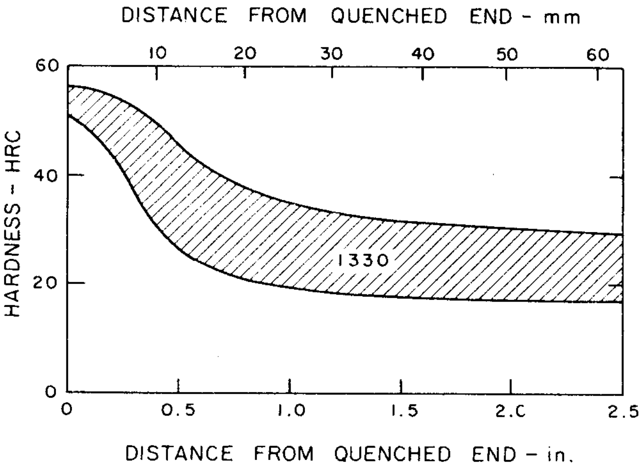


Fig. 14 End-quenched hardenability of manganese (1330) cast steel.

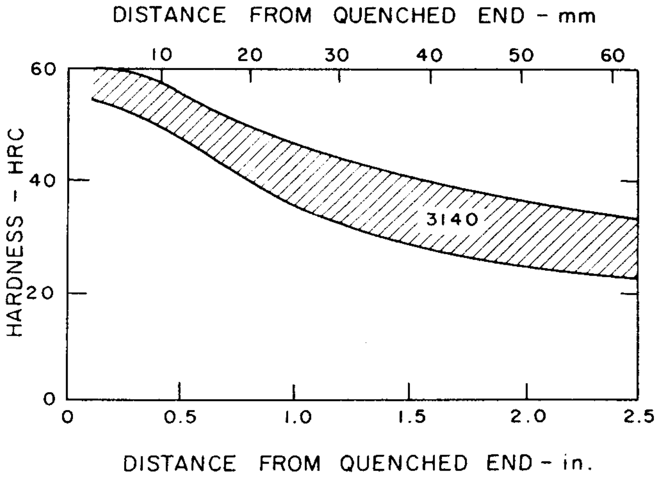


Fig. 17 End-quench hardenability band for nickel-chromium (3140) cast steel.

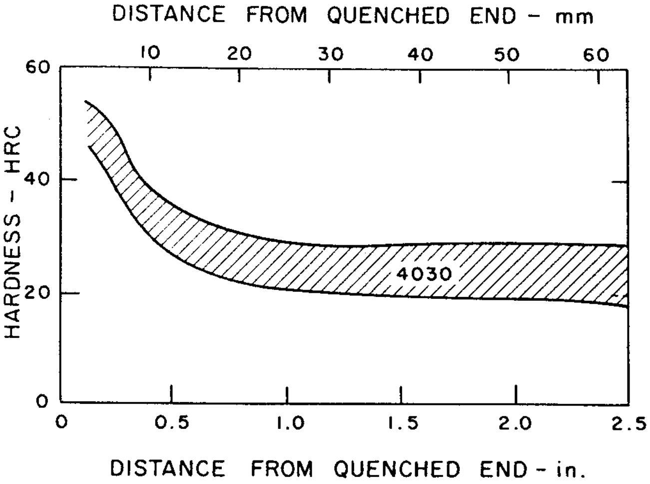


Fig. 18 End-quench hardenability of molybdenum (4030) cast steel.

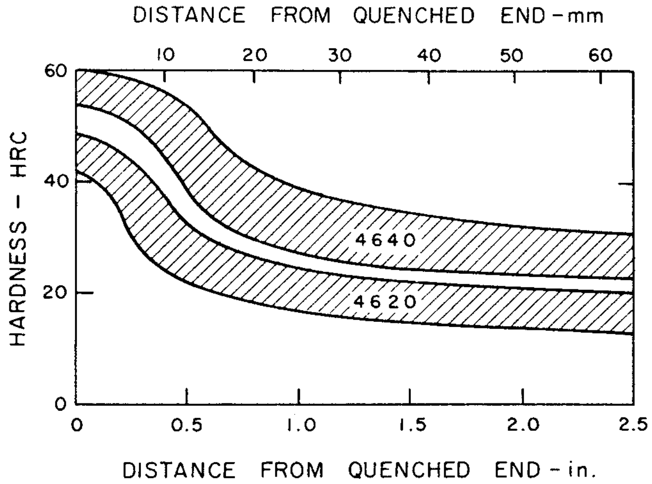


Fig. 21 End-quench hardenability of nickel-molybdenum (4620 and 4640) series cast steel.

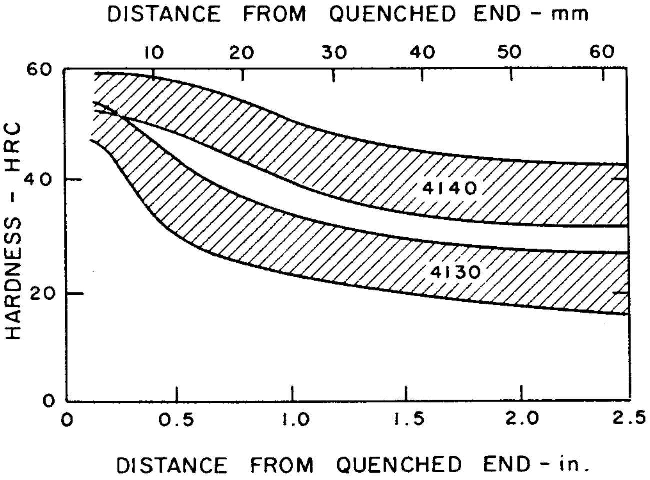


Fig. 19 End-quench hardenability of chromium-molybdenum (4130 and 4140) cast steel.

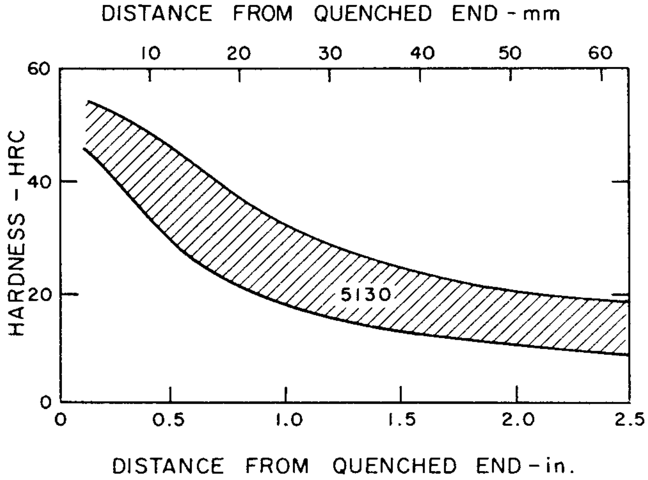


Fig. 22 End-quench hardenability of chromium (5130) cast steels.

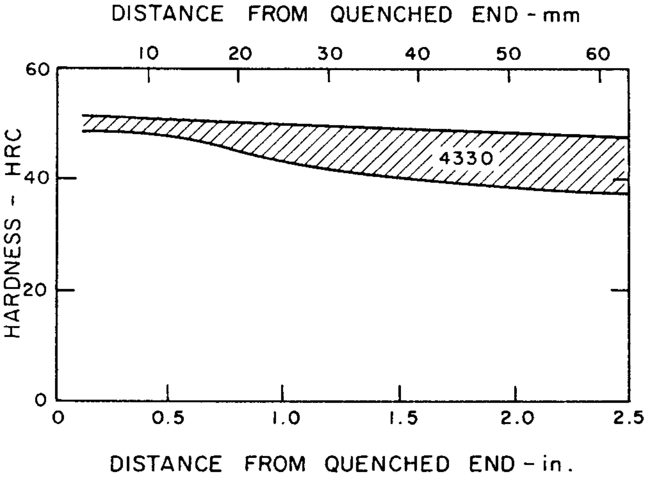


Fig. 20 End-quench hardenability of nickel-chromium-molybdenum (4330) cast steel.

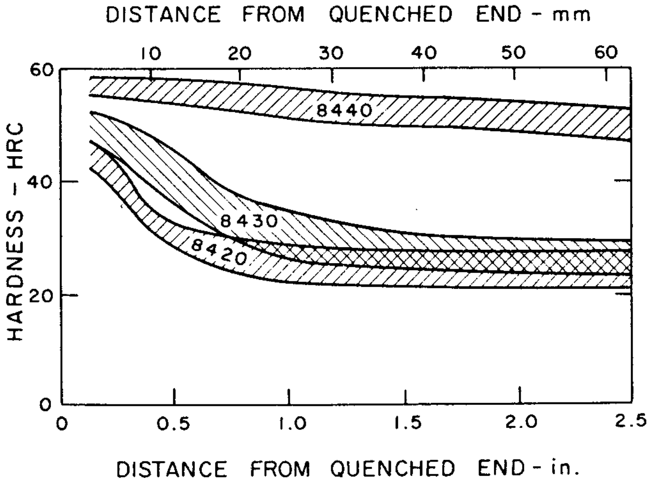


Fig. 23 End-quench hardenability of manganese-molybdenum (8400) series cast steels.

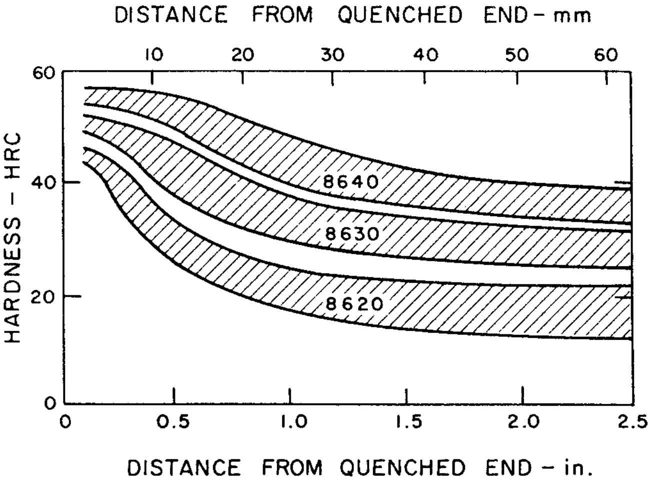


Fig. 24 End-quench hardenability of nickel-chromium-molybdenum (8600) series cast steel.

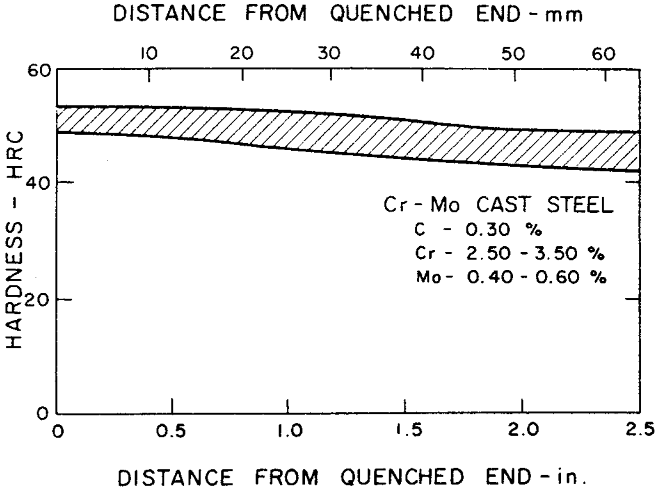


Fig. 26 End-quench hardenability band for 2.50 to 3.50% chromium, 0.40 to 0.60% molybdenum cast steels.

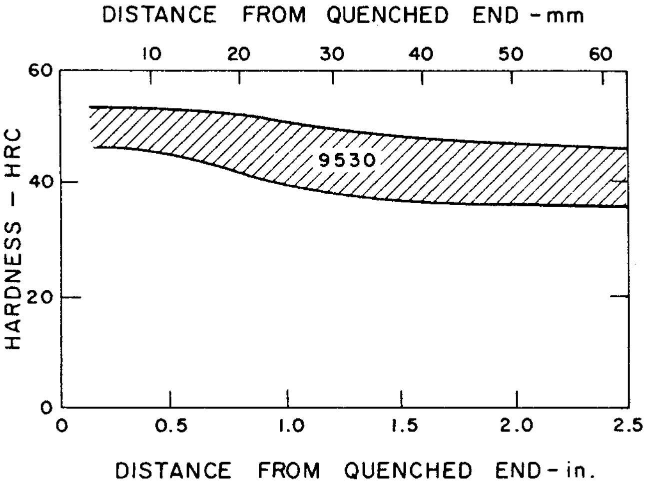


Fig. 25 End-quench hardenability of manganese-nickel-chromium-molybdenum (9530) cast steel.

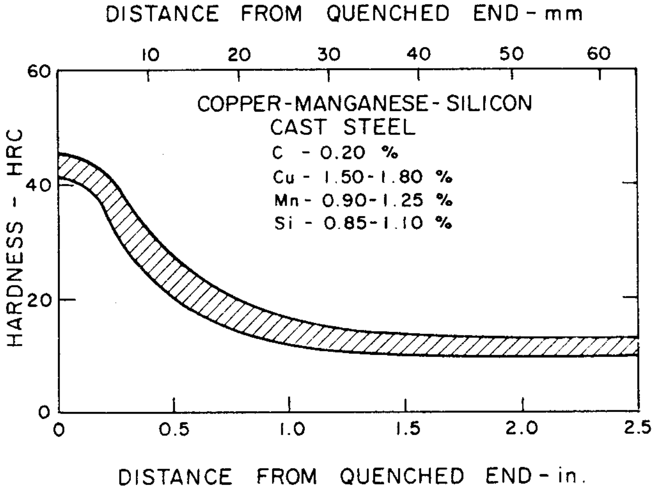


Fig. 27 End-quench hardenability of copper-manganese-silicon cast steel.

Many of the figures show the effect of carbon in alloys where the rest of the analysis is constant.

Figures 28, 29 and 30 show the effect of boron on the end-quench band. This effect is obtained by the presence of 0.001 to 0.006% boron. Excessive additions of boron are not recommended because of the possibility of boride or carboboride formation and the effect of these compounds on casting and mechanical properties.

The bands are useful in selection of an alloy or several alloys for given applications.

Part of the width of the band for a given alloy is due to unavoidable variations in analysis from heat to heat. To some degree it is due to residual elements. If an element, for instance chromium, is present as a residual, its presence will have an appreciable effect on hardenability. It follows that residual alloying elements must be watched and controlled as closely as specified elements if the hardenability band is not to widen.

The hardenability band for a wrought steel will be the same as that for a cast steel if both the wrought steel and the cast steel have essentially the same analysis and grain size.

Application of Hardenability Concepts in Alloy Selection

Alloy Content. The composition of a steel is an important factor of hardenability. Carbon is one element which is present in every steel and its effect on hardenability must be considered along with its effect on as-quenched hardness.

Increasing carbon increases hardenability as shown by Figure 4 and by Figures 12 and 13. The effect of carbon on hardenability is comparatively slight. Figure 31 shows that the hardness of martensite increases with higher carbon contents. It also shows that the hardness increases with increasing percent martensite at constant carbon content. From the data in Figure 31 and the end-quench bands in Figure 12, it can be shown that 1020 steel will contain 50% martensite at about 2/16 in. (3.2 mm) from the quenched end, whereas the 50% martensite point for

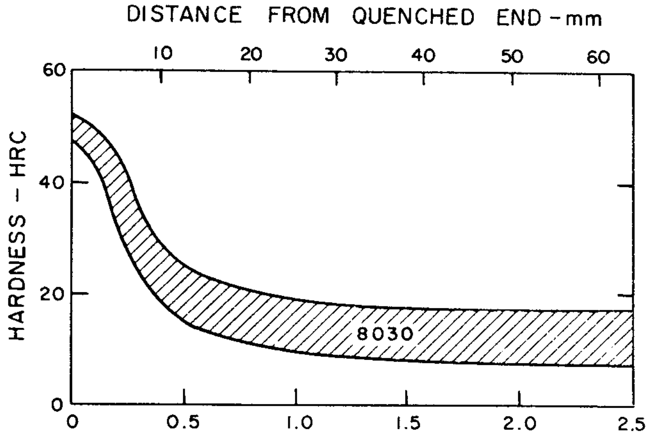


Fig. 28 End-quench hardenability of manganese-molybdenum (8030) cast steel.

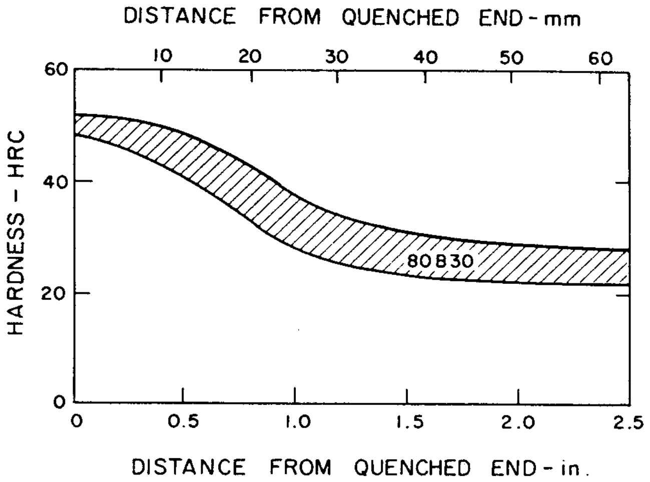


Fig. 29 End-quench hardenability of manganese-molybdenum-boron (80B30) cast steel.

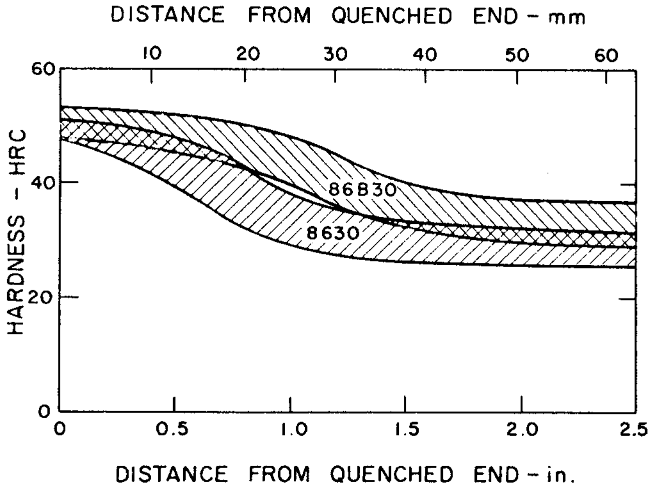


Fig. 30 End-quench hardenability of nickel-chromium-molybdenum-boron (86B30) cast steel as compared to 8630 cast steel.

1040 steel is at 5/16 in. (8 mm) from the quenched end. Doubling the carbon content increases hardness, but raises hardenability only slightly.

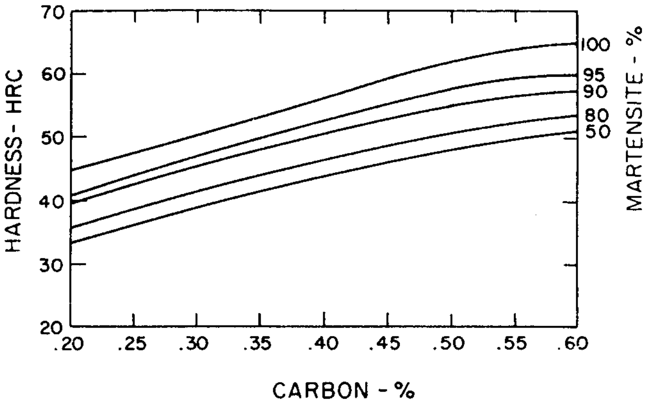


Fig. 31 The effect of carbon on as-quenched hardness. The percent martensite present at any point can be determined by matching the carbon content of the steel with the hardness measured at that point using this graph.

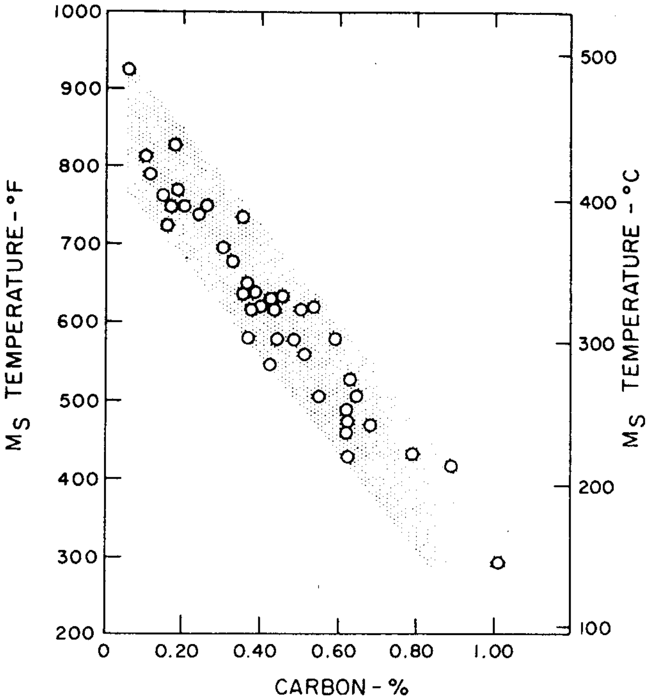


Fig. 32 Effect of carbon content on M_s temperature for 44 widely used carbon and alloy steels (**8**).

One disadvantage of increasing carbon is its effect on M_s, the temperature at which martensite starts to form. Figure 32 shows the relationship of the M_s temperature to the carbon content (**7**). The data are for both carbon and low alloy steels indicating that the lowering of the M_s temperature is primarily a matter of carbon content. Steel is less plastic at a lower M_s temperature and less able to accommodate the volume change of about 1.5% which is associated with the transformation to martensite. Moreover, the higher-carbon martensite is harder and more brittle than low-carbon martensite; higher stresses, and sometimes distortion and cracking, therefore result.

Since varying the carbon content alone cannot produce the hardenability required by many applications, alloying elements are added. The effects of several important alloying elements on hardenability

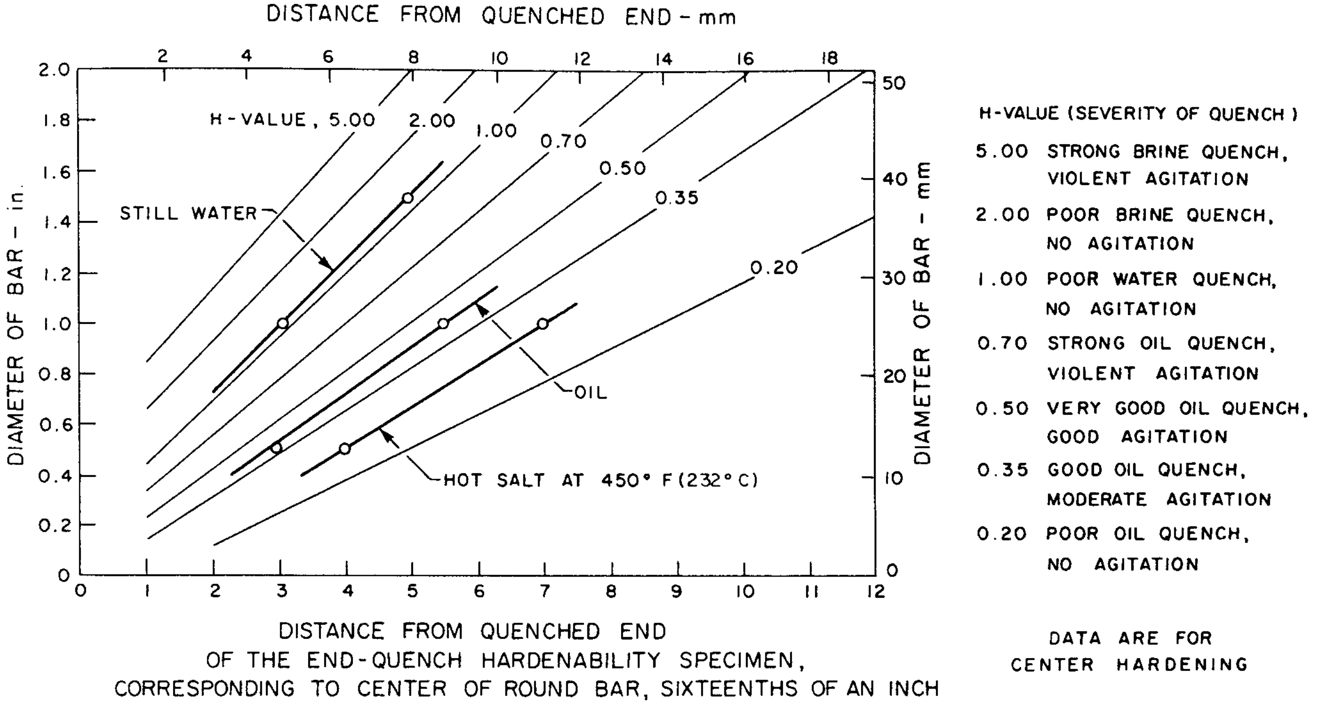


Fig. 33 Grossmann chart relating bar diameter, hardenability of steel, and severity of quench (*H*-value). See text for discussion of method for using this chart to evaluate severity of quench **(6)**

are illustrated in Figure 5. A virtually unlimited number of alloy combinations could be visualized due to the large number of possible combinations of carbon and alloying elements. The actual choice of alloying elements, i.e. of the grade of steel, depends, however, on a number of practical considerations. Cost and availability of the element must be considered. Cost related factors will include raw materials, melting loss, and reliability of the addition. In all cases the carbon content should be only high enough to produce the strength and hardness required by the application.

Unless there is some overriding reason to specify a given alloy, first consideration should be given to a grade which has appropriate hardenability and which is already in production in the foundry that will produce the castings. Use of such an alloy will simplify the procurement of castings because it will make use of the foundry's experience and will not require the foundry to integrate another alloy into its production schedules. This last point is important when small numbers of castings are ordered.

Quench Severity. The Grossman chart (Figure 33) can be used to obtain *H* values for quench severity under operating conditions **(6)**. As an example of the use of the chart, the hardness at the center of a 1.2-in. (30.5 mm) diameter bar quenched in still water ($H = 1.0$) will be the same as the hardness 4/16 in. (6.4 mm) from the quenched end of the end-quench bar of the same alloy.

To determine the *H* value of a commercial quench, an end-quench bar and cylinders of two different diameters are needed. The cylinder diameters are chosen so that the center hardnesses will fall on the sloping part of the end quench curve. The samples and the end-quench bar can be made from a wrought steel rod. The analysis is selected to give a usable end-quench curve.

The two cylinders are quenched with a load of castings. In the example in Figure 33 for still water quench, the hardness at the center of the 1.5-in. (38.1 mm) diameter bar equalled that at 5/16-in. (8 mm) from the end of the end-quench bar. The hardness at the center of the 1-in. (25.4 mm) diameter bar was equivalent to 3/16-in. (4.8 mm) from the quenched end of the end-quench bar. These two points and a line joining them are plotted in Figure 33. The *H* value of this quench is slightly over 1.0. The curves for oil and hot salt were determined in the same way.

Methods **(8)** have been devised which can be used to estimate the hardenability required to achieve the desired hardness and microstructure at critical locations of a casting of given size and configuration in a production quench. The best method consists of correlating end quench hardness data with equivalent hardness locations in the shape of interest. Figure 34 illustrates this method.

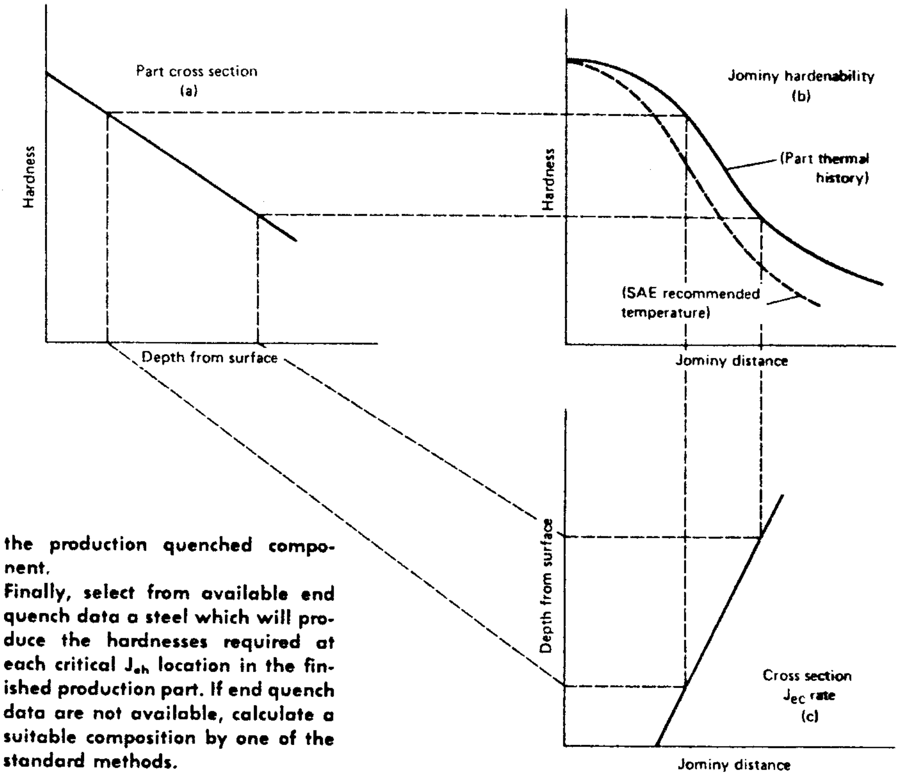
Changes in the quenching medium can seriously affect the *H* value. An increased temperature reduces the cooling effect of water, but has little effect on that of oils. The water temperature is not important up to 75°F (24°C) but between 75 and 120°F (24 and 49°C), the cooling power decreases materially. Above 120°F (49°C) the cooling power of water is quite low.

Dissolved salts increase the cooling power of water, while emulsions reduce the cooling rate that can be obtained.

Fig. 34 Determination of Jominy equivalent cooling (J_{eh}) rates

Jominy equivalent cooling (J_{eh}) rates are determined by comparing hardnesses of cross sections of parts receiving the established production heat treatment to hardnesses obtained on end-quenched bars of the same steel. A typical procedure is as follows:

1. **Select hardening and quenching conditions which your production hardening equipment can fulfill easily.**
2. **Select a low hardenability steel, such as 8620, 4023 or 1040, and manufacture a quantity of finished components: gears, bearings, shafts.**
3. **Quench a number of these components (in the uncarburized condition) in the production facility.**
4. **Measure hardnesses obtained at all critical locations from the surface to the core.**
5. **Compare the measured hardness values at these locations with equivalent hardness values produced at some end quench (J_{eh}) location on a Jominy bar made from the same heat and end quenched from the same thermal conditions.**
6. **The J_{eh} values obtained in this fashion define the equal hardness cooling conditions for each location in the production quenched component.**
7. **Finally, select from available end quench data a steel which will produce the hardnesses required at each critical J_{eh} location in the finished production part. If end quench data are not available, calculate a suitable composition by one of the standard methods.**



Raising the temperature of oil quenches to 150°F (66°C) raises the cooling rate slightly. Higher temperature of oil quenches results in lower viscosity and less drag out (the amount of quenching medium that fails to drain from the component upon removal from the quench tank). The temperature, however, should never be higher than 50°F (28°C) below the flash point of the oil for safety reasons.

Contamination of oil with small amounts of water noticeably increases cooling rate. Breakdown of the oil may also speed up cooling. Both of these conditions are undesirable.

There are tests such as the hot wire test or the magnetic test that can be used to indicate changes in the quenchant. A periodic check using the Grossman chart can also show changes in the *H* value. This test is preferred since it is simple and is performed under operating conditions.

Heat Treatment. The choice of heat treatment, alloy content and hence hardenability determine the mechanical properties of steel. Hardness is rarely a design property; however, it is useful as an inspection tool because it relates to the mechanical properties.

Before discussing hardenability-related considerations in selecting the method of heat treatment, it is necessary to define certain important heat treating terms.

The heat treatment conditions which are frequently referred to are "quenched and tempered" and "normalized and tempered." These terms will be defined below under Heat Treatment in terms of the operations.

Tensile strengths up to 90 or 95 ksi (621–655 MPa) are usually produced by normalizing and tempering but for strengths of 95 ksi (655 MPa) and higher, quenching and tempering must be employed. However, quenching can be used for tensile strengths below 90 ksi (621 MPa). This is done where the improvement in other properties is required.

Quenching, as compared to normalizing, results in a higher yield/tensile strength ratio and higher ductility for a given tensile strength. At a given strength level, impact values at room temperature are better in quenched steels and are much better at low temperatures.

Despite the advantages derived from quenching, normalizing should not be overlooked. Normalizing is less expensive than quenching, particularly oil quenching, and presents less tendency to distortion and cracking. If the properties required by service conditions demand quenching, there are steps to be taken to decide whether or not a given alloy is applicable.

First, it should be noted that higher carbon steels are usually oil quenched rather than water quenched. Having decided between water and oil quench, the next step is to refer to Figure 10 to get the end-quench-equivalent distance for various points in the section.

Next, the lower limit of the hardenability band will give the hardness traverse of the section. Finally, Figure 31 will give the martensite content at various points in the cross section.

As described below, it is seldom necessary or desirable to quench to 100% martensite at the center of a section.

Quench Cracking does not often occur in sections which are thin, but in sections above 1 in. (25.4 mm) it can take place when through hardening occurs. Parts with abrupt section changes are particularly prone to cracking because of stresses which develop during the quenching operation.

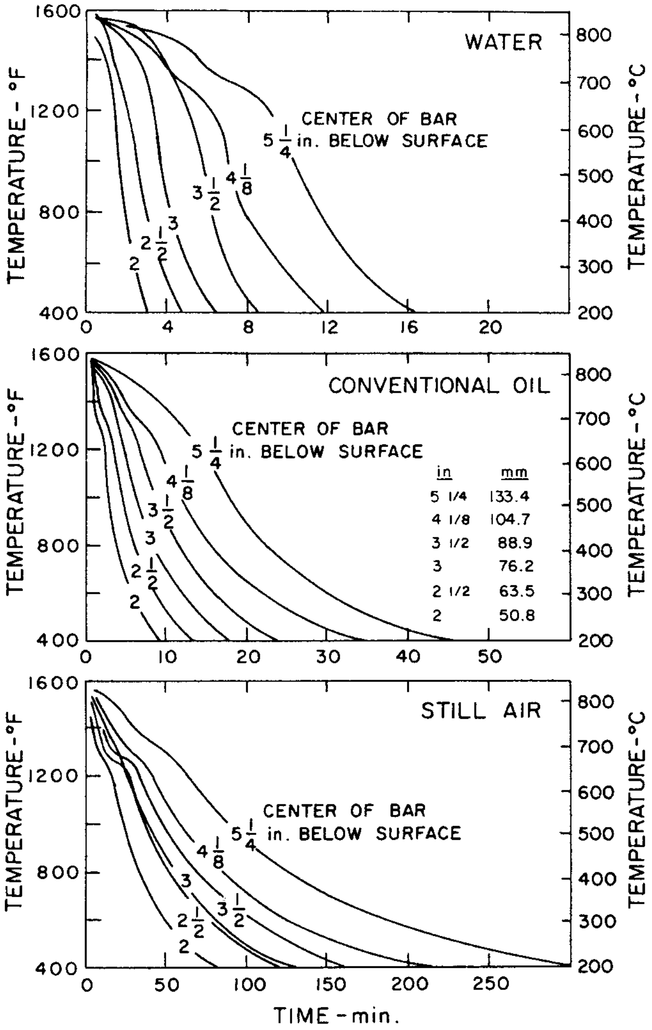


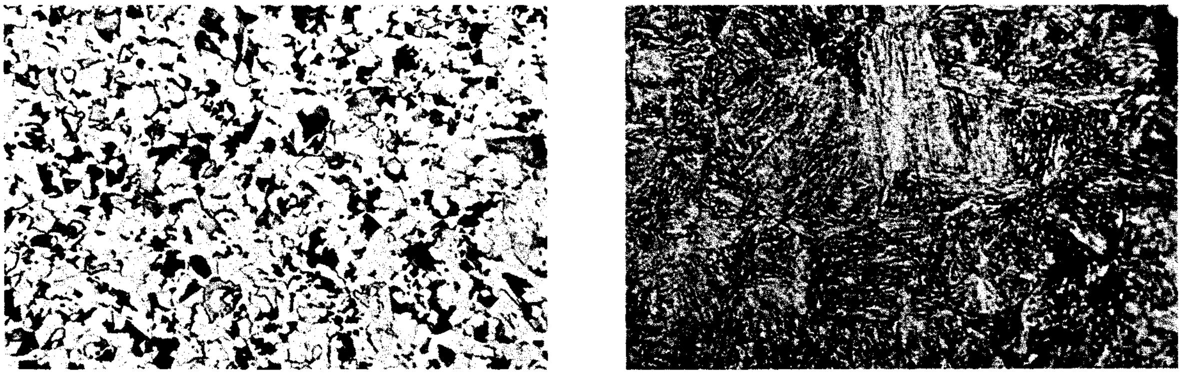
Fig. 35 Effect of section size on cooling curves (**6**).

Figure 35 shows the cooling curves for the center of different size bars for water and oil quenching and normalizing. The cooling rates indicated by these curves are fast enough to produce through hardening with many alloy steels, particularly for smaller diameters. This could lead to quench cracking.

A section is considered through hardened if there is no less than 90% martensite at the center. Through hardening followed by tempering would insure the best combination of mechanical properties, but it has some drawbacks. Alloy cost, the use of more expensive oil quenching, and the danger of cracking should be considered.

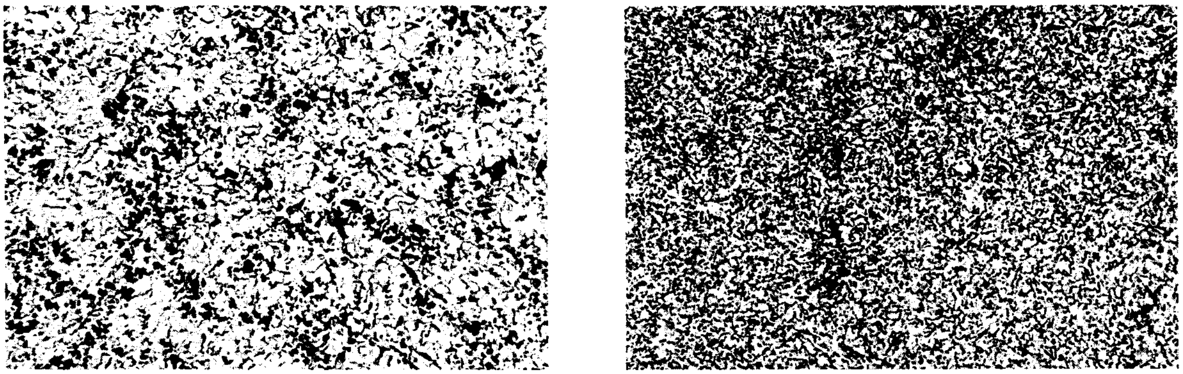
Hardenable alloys have been used in applications where through hardening occurred and where quench cracking was found. This has led to the erroneous conclusion that cracking tendency is a function of hardenability only. Cracking is due to the stresses developed by the volume change of the martensite transformation, the extent of this transformation, the design of the component, and its composition.

Fortunately, through hardening is seldom necessary. In wear applications where wear is from one side,



A 100× B 250×

Fig. 36 A. Ferrite-pearlite structure (light and dark constituents respectively) of normalized 0.2% C Steel. B. Martensite structure of quenched and tempered Ni-Cr-Mo (8635) steel.



A 100× B 100×

Fig. 37 A. Ferrite pearlite structure of 1-in. (25.4 mm) thick plate casting of 0.20% C steel obtained by normalizing. B. Same as in A, but finer, obtained by quenching and tempering.

Representative
Properties:

										C_v – Impact Energy					
		UTS		YS		El	RA	NDTT		RT		0°F(–18°C)		–60°F (–51°C)	
	BHN	ksi	MPa	ksi	MPa	%	%	°F	°C	ft·lb	J	ft·lb	J	ft·lb	J
A	149	77	531	51	352	31	60	–45	–43	80	108	65	88	28	38
B	163	81	558	57	393	27	61	–65	–54	100	136	78	106	29	39

through hardening is desirable but not always obtainable. Most cast sections are subjected to torque or bending. Here the center of the section carries little or no stress and there is no reason to require through hardening.

Hardenability data aid in the selection of an alloy to use available quenching equipment to produce a cast section with the desired microstructure and mechanical properties.

Microstructure and Properties. The type of metallurgical structure that a given heat treatment produces depends to a large extent on alloy content, i.e. hardenability, as well as the section size being heat treated, and the specific location within a given section.

A ferrite-pearlite structure will form upon normalizing most carbon steels and many low alloy steels (Figure 36 A); martensite forms upon quenching provided the cooling rate is high enough for the particular alloy composition (Figure 36B).

Even though quenching may not produce martensite the resultant structure will be finer and typically produce superior toughness. These difference are illustrated for low hardenability carbon steel in Figure 37 A and B.

The location within a given component, or section, may have small or large effects on structure and properties—depending on hardenability. For carbon steel (Figure 38) minor differences are noted in the ferrite-pearlite structure of a 4-in. (101.6 mm) thick A216-WCC type carbon steel plate that was quenched and tempered. The hardness at the surface, 1/4 T, and center locations was BHN 163, 142, and 137, respectively. The toughness, in terms of Nil Ductility Transition Temperature, NDTT, was —40, —30, and —20° F (—40, —34, and —29° C), respectively.

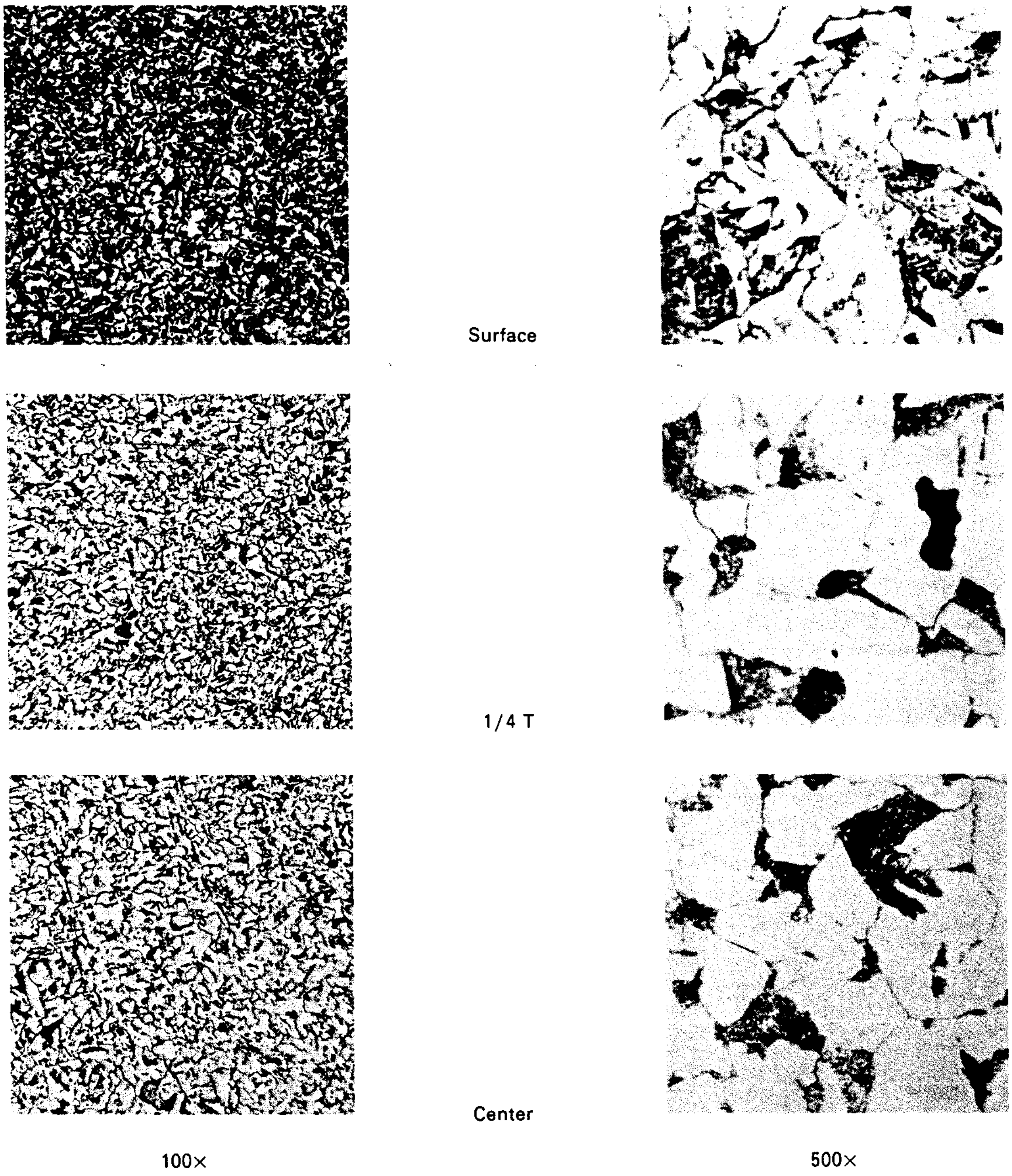


Fig. 38 The ferrite-pearlite structure of a quenched and tempered 4-in. (102 mm) thick, A-216-WCC type, carbon steel plate casting.

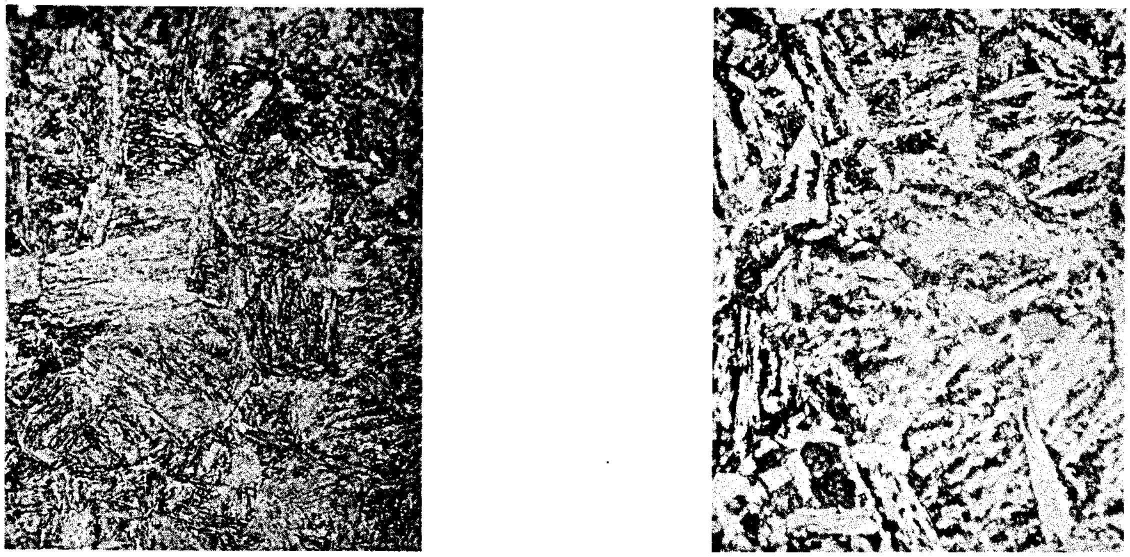
Quite pronounced microstructural and mechanical property differences are to be expected when sections are quenched and do not through harden due to insufficient hardenability. An example is shown in Figure 39 for a 17-in.-(432 mm) thick gear blank of cast 8635 steel that was quenched and tempered. Near-surface areas were martensitic while a structure of acicular ferrite-pearlite was observed for locations 8.5 in. (216 mm) from the surface. Data in Figure 39 illustrate relatively small effects on strength—but major changes in ductility and toughness.

The dramatic differences in structure and mechanical properties of the preceding example are not observed when the composition of the steel is selected to provide a hardenability that causes through hardening. Uniformity is also achieved when the hardenability is insufficient to produce martensite in any part of the quenched component. Such situations often apply to carbon steel castings such as illustrated in Figure 37 and to low alloy steels as illustrated in Figure 40 for the normalized and tempered turbine blade casting with sections from 1-1/2 to 28 in. (38-711 mm) thick.

HEAT TREATMENT

The heat treatment is an important step in the production of steel castings because it develops the mechanical properties of a hardenable steel. For austenitic stainless steels the heat treatment is important to optimize corrosion resistance.

Several types of heat treatment exist. The essential

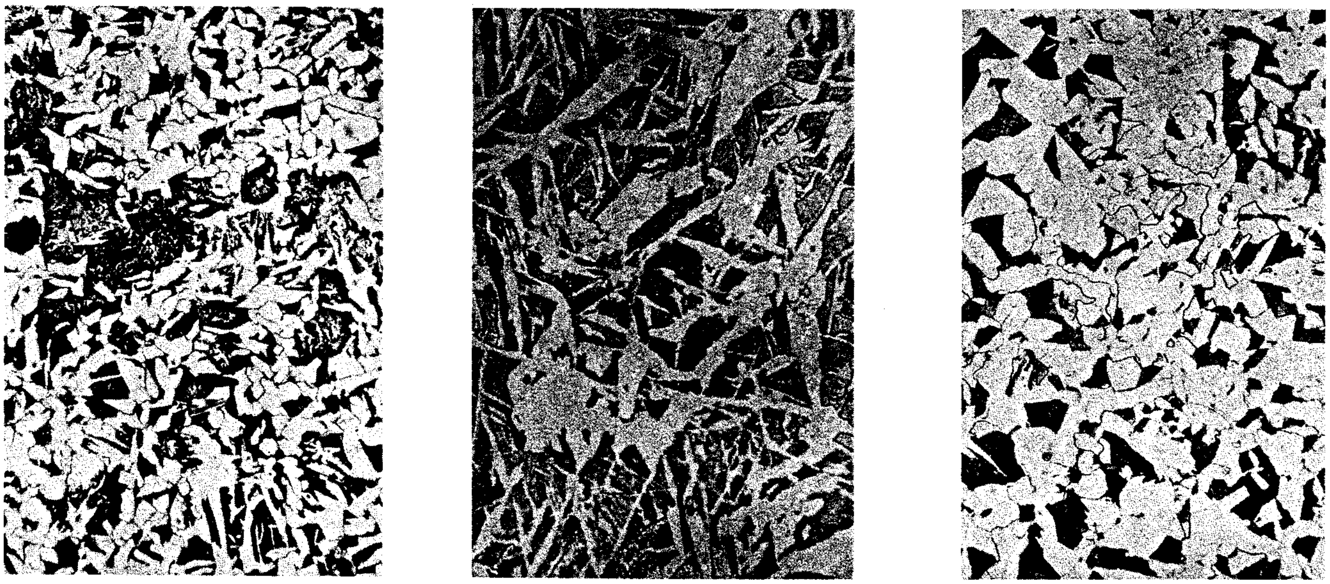


A 250× B 250×

Fig. 39 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



A 100× B 100× C 100×

Fig. 40 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

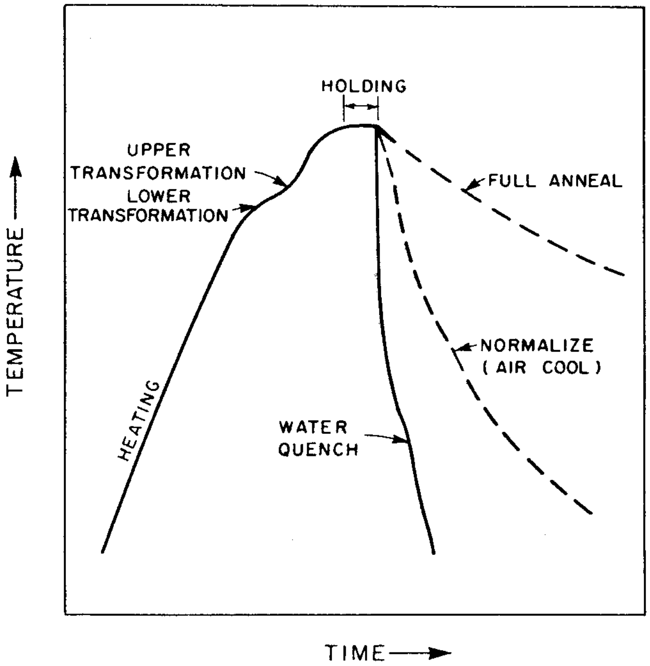


Fig. 41 A generalized sketch of the steps in the heat treating of steel castings.

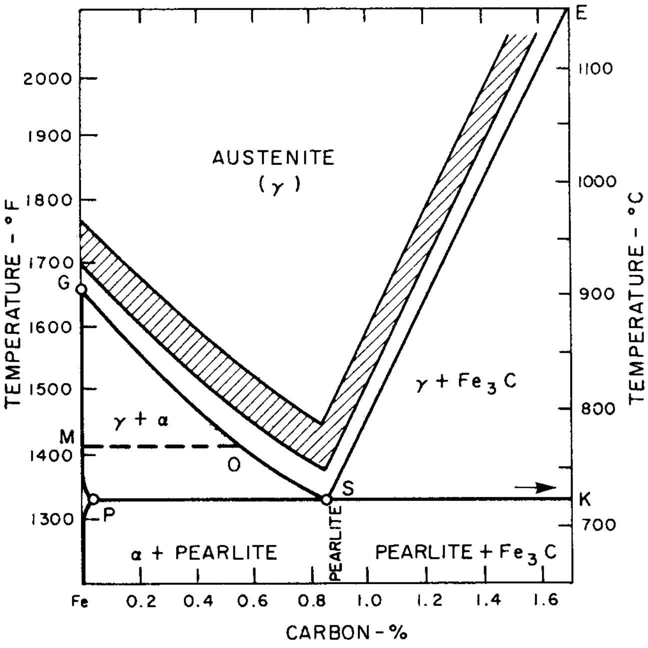


Fig. 42 Normalizing temperatures for carbon steels.

elements of any heat treatment are the heating cycle and the cooling cycle. Figure 41 shows schematically a heating cycle and three different cooling cycle types. The length of time that a casting is held at temperature and the cooling rate are important factors. The holding time should be long enough to complete the microstructural transformation that is desired.

Annealing

Annealing is practiced on low carbon steels to provide a soft, readily machinable structure. The strength of annealed castings is low, but ductility is high. Low alloy steels may be annealed for machinability and given a final heat treatment later.

In a full anneal the castings are heated above the upper critical temperature, held there long enough to complete the transformation to austenite, and then furnace cooled at a controlled rate to obtain a stress-relieved casting with a pearlite-ferrite structure that is ductile and readily machinable. There are variations of the annealing heat treatment for specialized purposes, for instance to achieve a spheroidized pearlite structure. Annealing temperatures of such specialized treatments may differ substantially from that of a full anneal. Full annealing and spheroidizing heat treatments are expensive and should not be specified unless the last increment in ductility is actually required.

Cooling is accomplished by reducing, or simply turning off, the heat input to the furnace. When the castings have cooled to below the lower critical temperature, about 800°F (427°C), the transformation of austenite is usually complete. The castings should then be removed from the furnace and air cooled or even quenched. Furnace cooling to lower temperatures merely wastes furnace time and requires extra heat to bring the furnace up to temperature for the next load.

Normalizing

Normalizing consists of heating the steel to a suitable temperature above the upper critical transformation temperature (Figure 42), holding long enough to complete the transformation to austenite, removing the work from the furnace and cooling it in still air. Some castings are tempered after normalizing.

The castings must be placed so that the air can circulate freely around every casting. If air flow is restricted, the operation will be more like annealing. On the other hand, accelerated cooling by fans or forced-air flow may produce a result more like quenching.

The microstructure that results from normalizing is a mixture of ferrite and pearlite, associated with only low residual stresses and almost no distortion.

Tensile strengths up to 95 ksi (655 MPa) can be obtained in this way. Normalizing and tempering is used to meet a number of standard specifications in this strength range. Because of the uniform structure obtained upon normalizing, machinability is good.

The cost of normalizing makes this heat treatment attractive. It requires less furnace time than annealing and its cooling cycle is less expensive than quenching.

Hardening by Quenching

In hardening by quenching, the work is heated above the transition temperature (austenitized) as in annealing or normalizing (Figure 43). The work is cooled more rapidly than in the other heat treatments—fast enough so that pearlite and ferrite do not have time to form (Figure 1). There are, however, air hardening grades of steel which do not require accelerated cooling by quench-

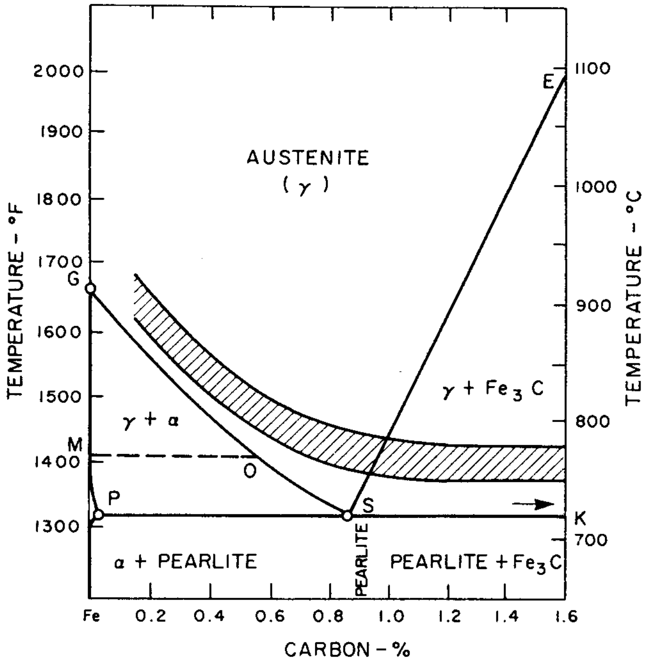


Fig. 43 Hardening temperatures for carbon steels.

ing in water or oil. Prominent examples are the 13-Cr steel grade CA-15 and the 13Cr-4Ni steel grade CA-6NM. Certain low alloy steels are considered air hardening in relatively thin sections.

Water and oil are the media most commonly used for quenching steel castings. Water is used whenever possible. Higher-carbon and deep-hardening steels require oil quenching. Some complicated shapes also demand oil quenching to minimize quench cracking.

Oil quenches a little more slowly than water at all temperatures. At lower temperatures the cooling curves for oil taper off, meaning even slower rates than for water. Thus martensite forms more slowly in oil than in water.

Certain organic chemicals can be added to water to give a quenching solution which resembles oil in its heat removal characteristics. The main advantage of these solutions is that they have the behavior of oil without the fire hazard of oil. Their greatest disadvantage is that they coat the work and so change the composition of the bath. The quench severity of these baths varies widely with small changes in composition. Tight control is necessary and difficult.

Quenching of carbon and low alloy steels is always followed by tempering. Tempering makes it possible to adjust the mechanical properties of quenched steel. The higher tensile strength levels of carbon and low alloy steels can be obtained only by quenching and tempering. Quenching and tempering produces the optimum combination of strength and toughness properties.

Other Quench Hardening Processes

Martempering and austempering are two quenching processes which harden the steel without producing as much stress, distortion, and cracking. These heat treatments are only rarely used for steel castings. There is also a modified martempering process or isothermal process. These three processes are diagrammed in Figure 44 along with the conventional quenching process. The cross-hatched areas represent the time-temperature combinations where transformations occur.

Austempering is of little importance in steel casting work. It is not practical for heavy sections as they exist in conventional sand castings. There may be some application for investment castings.

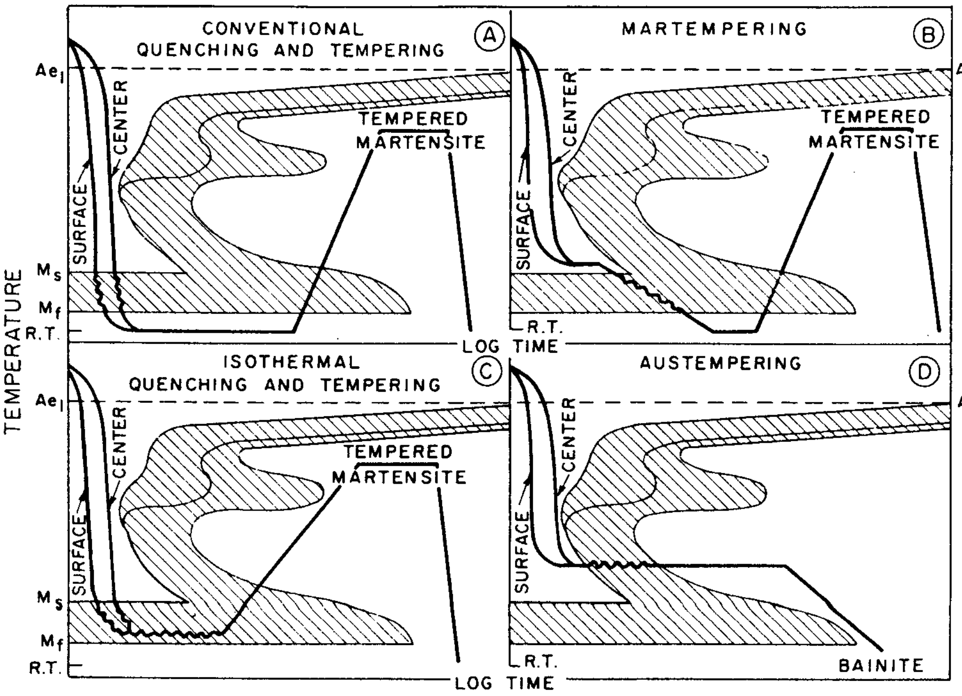


Fig. 44 Comparison of quenching processes.

TABLE 8 Temperature Range of Martensite Formation in Several Carbon and Alloy Cast Steels (9)

Steel SAE No.	Martensite Start (Ms). °F	°C	50% Martensite Formed °F	°C	99% Martensite Finish (Mf) °F	°C
1030	650	343	560	293	450	232
1065	530	277	425	219	300	149
1090	425	219	315	157	180	82
1335	650	343	560	293	450	232
2340	580	304	560	293	405	207
3140	635	335	550	288	430	221
4130	715	380	650	343	550	288
4140	650	343	570	299	440	227
4340	550	288	480	249	370	188
4640	650	343	570	299	480	249
5140	650	343	570	299	450	232
6140	620	327	560	293	450	232
8630	690	366	630	332	530	277
9440	625	330	540	282	405	207

In martempering, the work is quenched in a molten salt bath to a temperature just above the temperature where martensite begins to form (M_s). It is held in the salt bath long enough for the temperature to equalize in the heaviest sections. After that, the work is removed from the salt and air cooled. Martensite then forms between the M_s and the temperature at which martensite formation is essentially complete, M_s . Table 8 lists both M_f and M_s temperatures for a number of cast steels.

In modified martempering, the work is quenched into a bath at a temperature between the M_s and M_f temperatures. When the temperature at the surface and center of the work has equalized, the work is removed from the bath and either air cooled or placed in a tempering furnace.

In general, any steel that is usually oil quenched can be martempered. The maximum size section that will through-harden is appreciably less in martempering compared to conventional quenching.

Tempering

Tempering is a heat treatment which follows quenching or martempering, and sometimes normalizing. One purpose of tempering is to reduce the residual stress which develops during cooling and transformation. Another objective of tempering is to modify the metallurgical structure of martensite and thereby adjust strength and other mechanical properties to specified levels.

Tempering consists of heating the work to a temperature below the transformation range, holding for a specified time and finally, cooling. Carbon and low alloy cast steels are tempered in the range of 350 to 1300°F (177-704°C). The time of holding at temperature may vary from 30 minutes to several hours.

A longer time at a given tempering temperature, or a higher tempering temperature for a given time, produce greater tempering. The effects of temperature are shown in Figure 45 where hardness is used to measure the response to tempering.

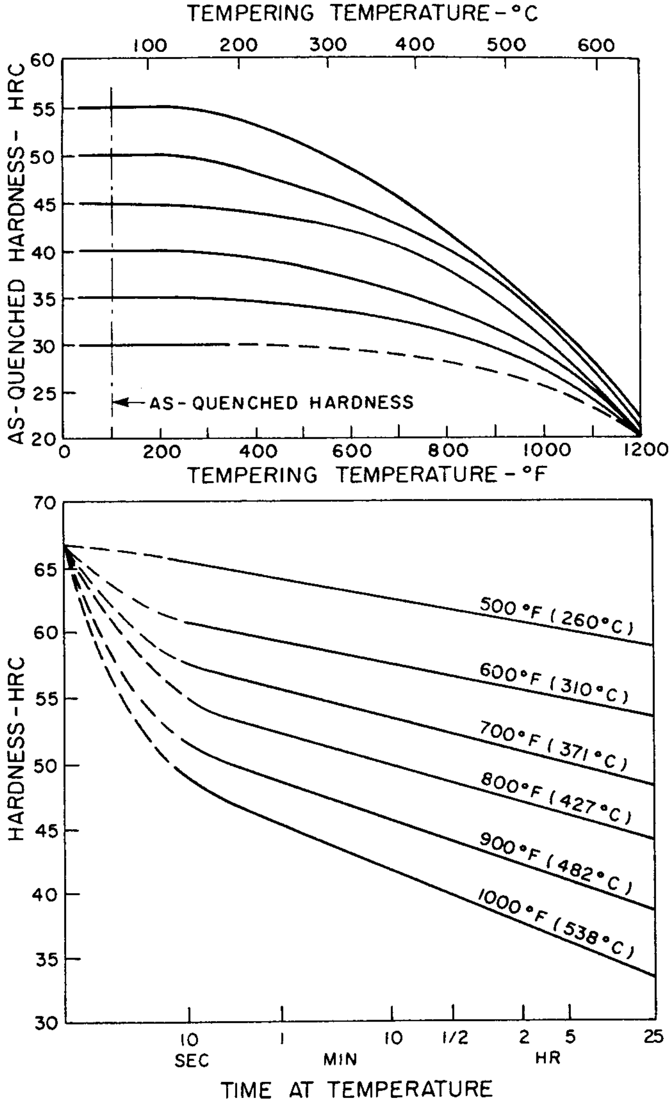


Fig. 45 Effect of tempering temperature and time on the softening characteristics of steel.

Martensite softens more than pearlite at a given tempering temperature. The composition also affects the tempering response; carbide-forming elements cause the steel to show greater resistance to tempering.

Tempering below 1100° F (593° C) may cause temper embrittlement in certain steels. The decrease in notch toughness is illustrated in Figure 46 for a Ni-Cr-Mo AISI 4320 steel, which contrasts the loss in toughness to tensile and hardness properties that are not sensitive to temper embrittlement. Usually tempering is not done in this temper embrittlement range and, when higher tempering temperatures are used, the work may be quenched from the tempering temperature to minimize time in the embrittling zone during cooling.

Stress Relief

Tempering is a stress relief treatment, so there is no need for a special stress relief after tempering. Stress relief is obtained by heating to temperatures above 500°F (260°C). Little or no stress relief occurs

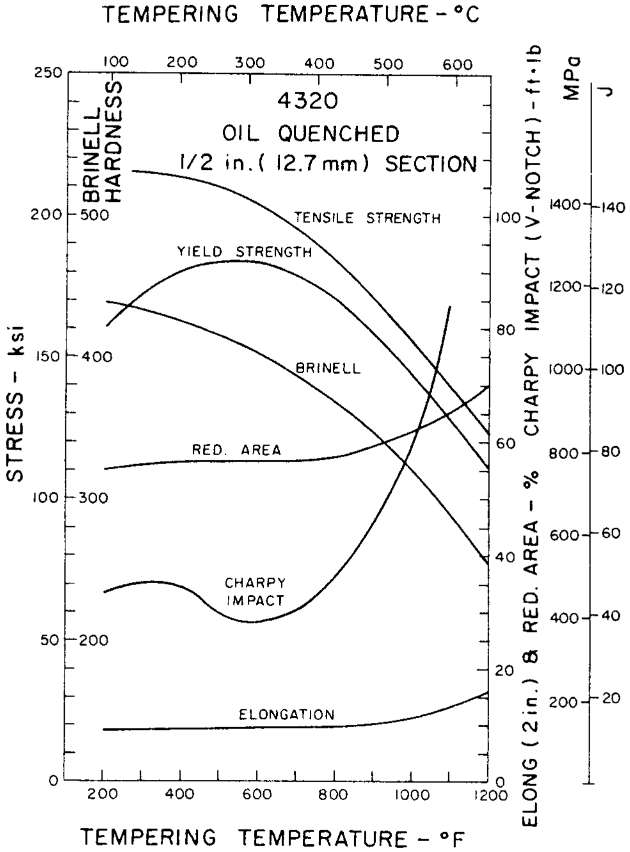


Fig. 46 Loss in room temperature toughness due to temper embrittlement, illustrated for wrought Ni-Cr-Mo steel (**10**).

below 500° F (260° C) for the example shown in Figure 47 where about 90% of the stress is removed at 1000° F (538° C). Sometimes a stress relief treatment is required when operations are performed after heat treatment which leave residual stresses in the casting. Welding, induction hardening, and grinding are examples of such operations.

The maximum temperature for stress relief is generally limited to 50°F (28°C) below the tempering temperature which had been used in heat treating the casting to prevent softening of the casting.

Hydrogen Removal

Hydrogen has been found to cause low elongation and reduction of area in steel. If the steel contains 4 or 5 parts per million of hydrogen, the ductility will be about 20% of that of a hydrogen free steel. Hydrogen in steel is a mobile element. At room temperature, the hydrogen will diffuse from the steel and ductility will be restored. This effect of aging is shown in Figure 48.

Hydrogen removal can be accelerated by heating to 400 to 600°F (204-316°C). This heat treatment is commonly referred to as aging. The aging time is proportional to section thickness. Generally, 1 in. (25.4 mm) equals 20 hr. For heavy sections, 10 in. (254 mm) or more, hydrogen removal by aging becomes impractical due to time requirements.

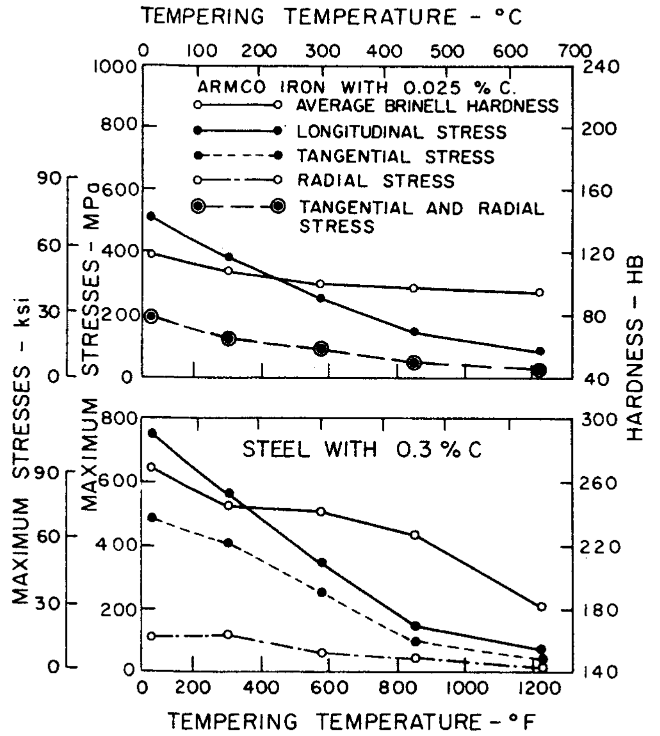


Fig. 47 The effect of tempering on residual stresses, in quenched cylinders (**11**).

Solutionizing

Austenitic stainless steels, austenitic manganese steels, and precipitation-hardening steels are solutionized. This heat treatment is sometimes referred to as "solution anneal" or "solution quench." In either case the object of the heat treatment is to dissolve second phases and to produce a homogeneous structure.

For austenitic stainless steels and austenitic manganese steels, this heat treatment produces austenite and dissolves carbides. A quench or other accelerated cooling is required subsequently (depending on alloy content and section size) to retain carbon in solution and prevent precipitation of carbides.

Solutionizing temperatures of austenitic stainless steels range from 1900-2100°F (1038-1149°C), depending on alloy content, section size, and corrosion resistance requirements. Austenitic manganese steels are commonly solutionized between 1850-1950°F (1010-1066°C) for best toughness properties, although higher temperatures are necessary for the higher carbon as well as alloy grades.

For precipitation hardening steels the solutionizing treatment creates a soft condition in which the steels can be machined with ease—compared to their hardened condition after aging. The cooling rate from the solutionizing temperature must be fast enough to prevent the precipitation hardening reaction from taking place. Examples of precipitation hardening steels are copper-bearing low alloy and also stainless steels such as CD-4MCu where aging treatments are sometimes chosen to achieve hardening on a controlled basis.

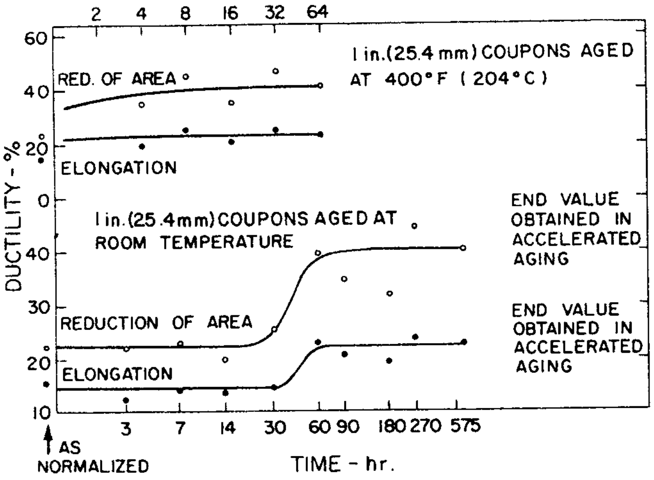


Fig. 48 Change in ductility with time for 1-in. (25.4 mm) coupons aged at room temperature and at 400°F (204°C). Values plotted are average of three tests.

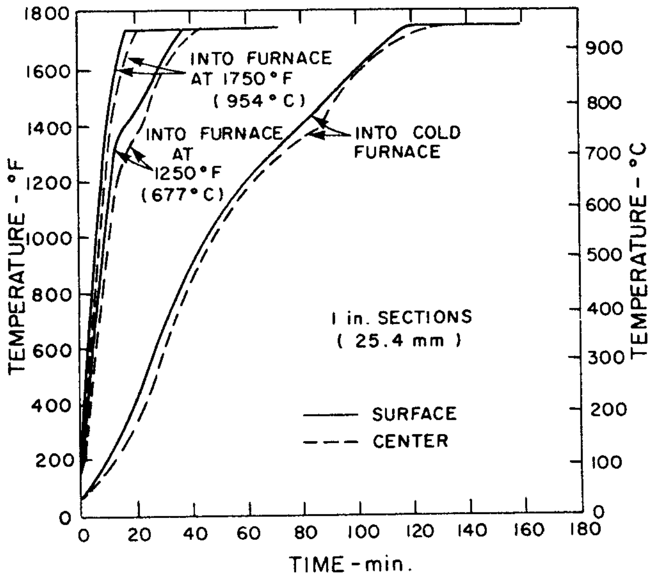


Fig. 49 Heating to 1750°F (954°C) of 1-in. (25.4 mm) section of low alloy steel.

Aging for Precipitation Hardening

Age-hardenable steels can be aged to harden at a controlled rate. One advantage of this type of hardening process is the absence of distortion when compared to that which normally occurs in steels that undergo a martensite reaction upon quenching. Another advantage is the ability to machine components in the soft, solutionized condition, followed by aging to harden the component at relatively low temperatures, without significant scaling. The hardening reaction in copper-bearing steels is based on reactions associated with, or leading to, the precipitation of a second phase from the copper-super-saturated steel. In maraging steels the aging reaction takes place in the martensitic structure and, among other alloying elements, is related to their content of titanium, aluminum, and niobium.

The manganese-copper cast steels are a family of low alloy cast steels which are precipitation hardened. These low carbon steels normally contain 0.90 to 1.50% manganese and 1.50 to 1.80% copper. At the lower end of the transition range, the copper is completely soluble, but at 1200°F (649°C), only 0.35% copper is soluble. The usual heat treating practice for these steels is to normalize from 1700°F (927°C) and precipitation harden for about two hours in the range of 900 to 950°F (482-510°C). This produces an increase of 20 ksi (138 MPa) in tensile strength with a minimum decrease in ductility.

Although quenching of the manganese-copper steels would produce the super-saturated solution of copper, it would also produce martensite. On tempering, the tempering reaction of martensite would mask the hardening effect of the aging reaction due to copper.

CB-7Cu and CD-4MCu are stainless precipitation hardenable steels. CB-7Cu, the equivalent of 17-4 PH and 15-5 PH, can be hardened by heating to 1925°F (1050°C) followed by cooling to room temperature and aging at temperature of 900–1150°F (480–620°C) depending on the desired properties. For CD-4MCu the solutionizing temperature is 2050°F (1121°C) with quenching from 1900–1750°F (1038–954°C). For applications involving corrosion, this alloy is usually employed in the solutionized condition. For purely structural applications aging treatments can be performed between 900–950°F (482–510°C).

Efficient Heat Treatment

Many years ago, heat treating instructions read, "place castings in cold furnace, bring slowly to temperature, hold at temperature for one hour per inch of section of the largest section."

The reason for bringing the work to temperature slowly was the belief that castings would distort or crack if heated rapidly. The reason for the one-hour-per-inch rule is not so clear. Factors were probably the assumption that the center of the section lagged behind the surface and that transformation was slow. Although the historic instructions have been relaxed slightly, there still exist some remnants of the wasteful practice.

As furnace construction and burner design improved, furnaces without cold spots became common. Some years ago, the Steel Founders' Society of America, acting through its Research Committee, conducted an extensive study of heat treating practice. This research takes on new importance in the current energy situation, and with the need for increased productivity.

The study involved sections up to 6 in. (152.4 mm) thick. The first part of the investigation concerned heating to a temperature above the transformation range. Temperatures were measured at the surface and center of the section. Production heat treating furnaces were used. Figures 49 and 50 show the results for 1- and 3-in. (25.4—76.2 mm) sections. Similar results were obtained for 6-in. (152.4 mm) sections.

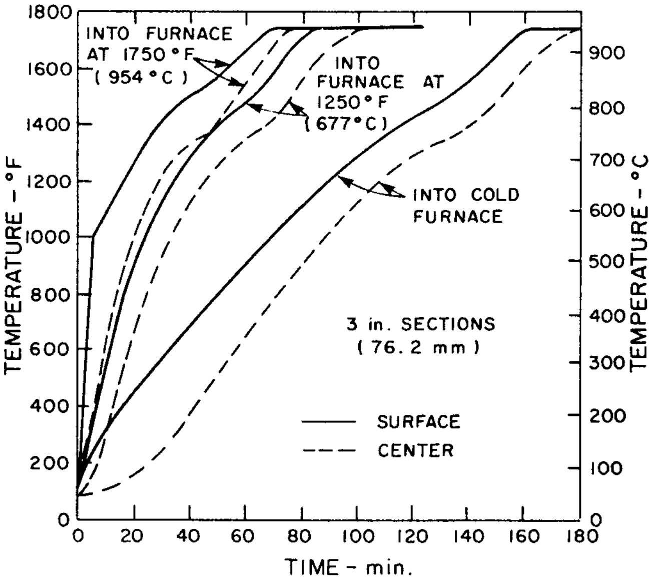


Fig. 50 Heating to 1750°F (954°C) of 3-in. (76.2 mm) sections of low alloy steel.

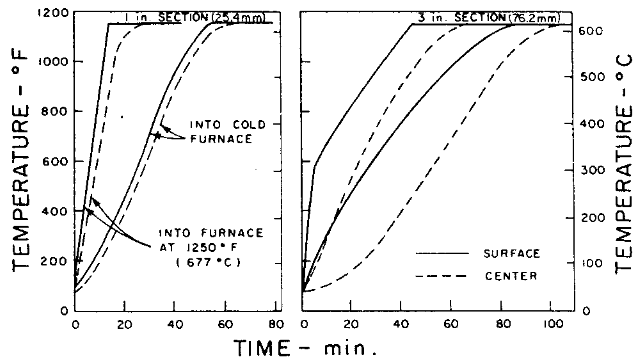


Fig. 51 1- and 3-in. (25.4 and 76.2 mm) sections heated to 1250°F (677°C).

The curves show that larger sections take longer to come to temperature than small sections do. When the surface approaches temperature, however, the center does not lag far behind. Also, Figures 49 and 50 show that time is saved by placing the load in a hot furnace.

The effect of holding time at the heat treating temperature was evaluated by measuring the mechanical properties after quenching and tempering. Holding times of 15 to 90 min, regardless of section size, produced the same properties. Holding times greater than 15 min produced no improvement. Normalizing before quenching was found to be ineffective for many common cast steel grades. Other grades require this heat treatment, especially to facilitate processing of the castings prior to quenching and tempering.

Figure 51 shows the heating curves for 1- and 3-in. (25.4 and 76.2 mm) sections heated to the tempering temperature. The temperature gradient between surface and center is small. Even in 6-in. (152.4 mm) sections the gradient is less than 100° F (56° C). Figure 51 also shows the time saved by charging the load into a hot furnace.

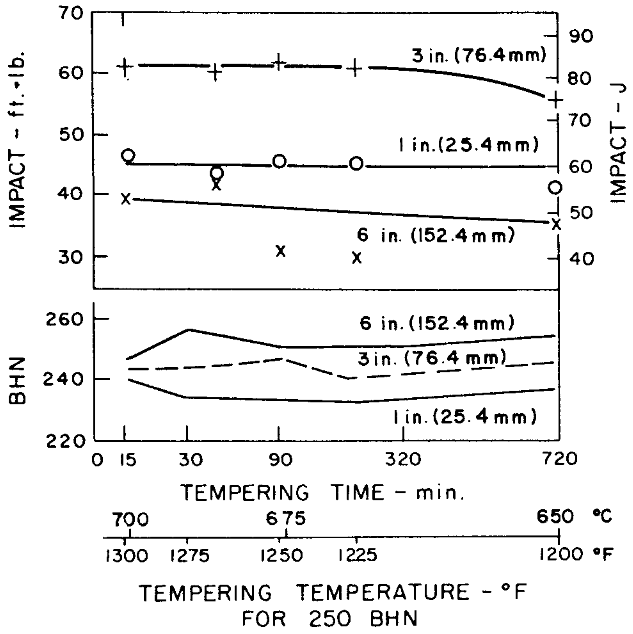


Fig. 52 Charpy V-notch impact properties of 1-, 3-, and 6-in. (25.4, 76.2, and 152.4 mm) sections of Ni-Cr-Mo cast steel at —40° F (—40° C) under conditions of constant hardness with varying tempering times and temperatures. Still water quenched.

Charpy V-notch impact tests at —40° F (—40° C) are sensitive measures of tempering. These and the Brinell hardness values in Figure 52, show that tempering for 15 min at 1300° F (704° C) produced the same effect as longer times at lower temperatures, up to 12 hours at 1200° F (649° C). This suggests short time, high temperature tempering treatment.

High alloy steels have a lower thermal conductivity than carbon or low alloy steels. Figure 53 shows the heating curves for a 6-in. (152.4 mm) section of 19Cr-9Ni steel introduced into a hot salt bath furnace. As shown by the temperature gradient curve, there is no serious gradient as the temperature of the work approaches the heat treating temperature.

For optimum corrosion resistance, high alloy steels must be heat treated to dissolve carbides. Research by the Alloy Casting Institute showed that solution was rapid at the proper temperature **(12)**. Figures 54 and 55 illustrate the corrosion test results on 19Cr-9Ni steels at three different carbon levels as a function of heat treat temperature and holding time. The extent of carbide dissolution was checked by the standard boiling 65% nitric acid test. Dissolution was slow at 1600° F (871° C) and incomplete at all carbon levels above 0.3% as indicated by the higher corrosion rate, or weight loss. At 1800° F (982° C) and higher temperatures, dissolution is complete in 5 min or less. Figures 53, 54, and 55 show that the heat treat time need not be more than 5 min after the whole casting has reached temperature.

In summary, the castings should be placed in a hot furnace, given time for the center of the section to reach temperature, held 15 min and then quenched or air cooled. The same practice is used in tempering. High temperature tempering and short times should

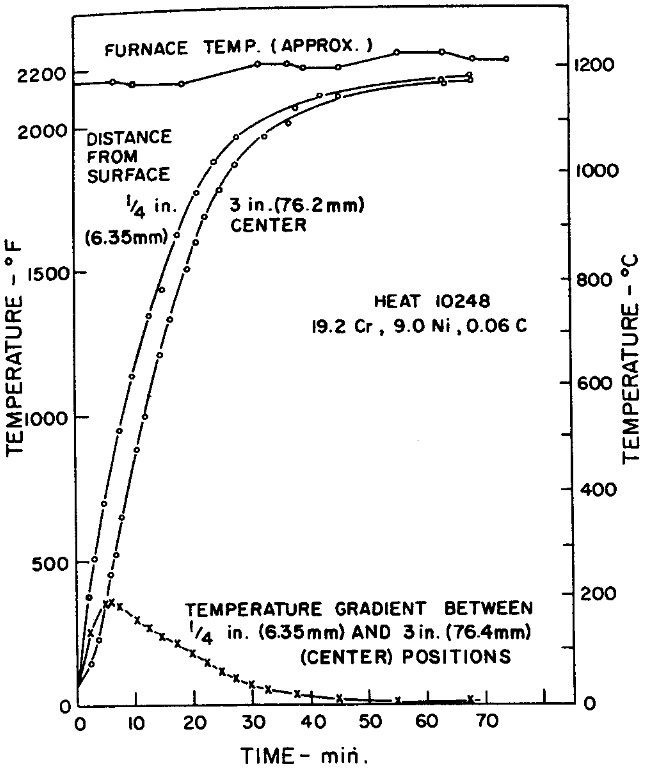


Fig. 53 Heating curves of 6-in. diameter cylinders of 19 Cr-9 Ni stainless steel containing 0.06% C.

be used. Quenching from the tempering temperature is recommended.

Fast heating has not been found to cause distortion or cracking although there may be rare designs which will not tolerate this practice.

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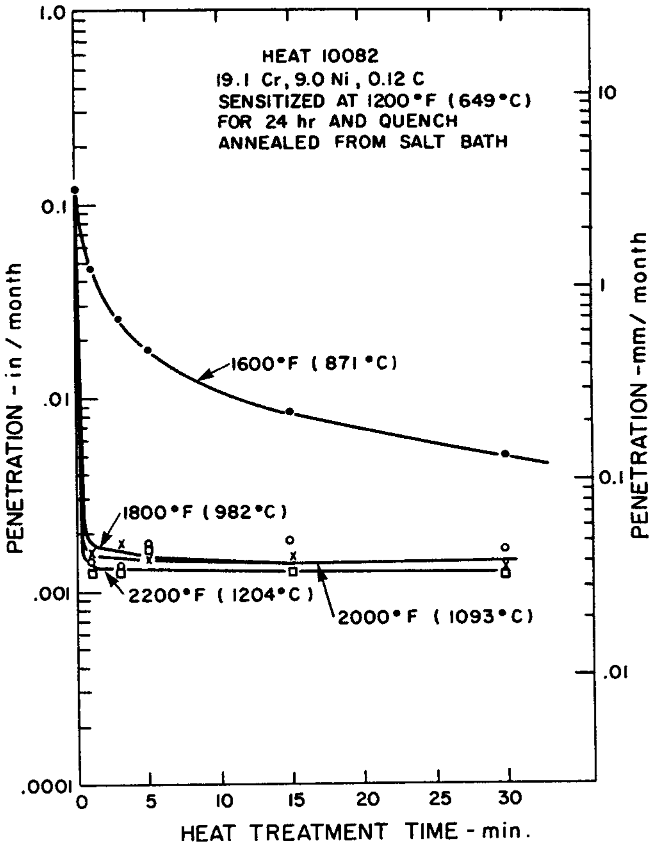

Fig. 54 Corrosion rates in nitric acid of 19 Cr-9 Ni stainless steel containing 0.06 and 0.03% carbon after heat treatment at 1600 to 2200°F (871 to 1204°C) for 1 to 30 minutes.

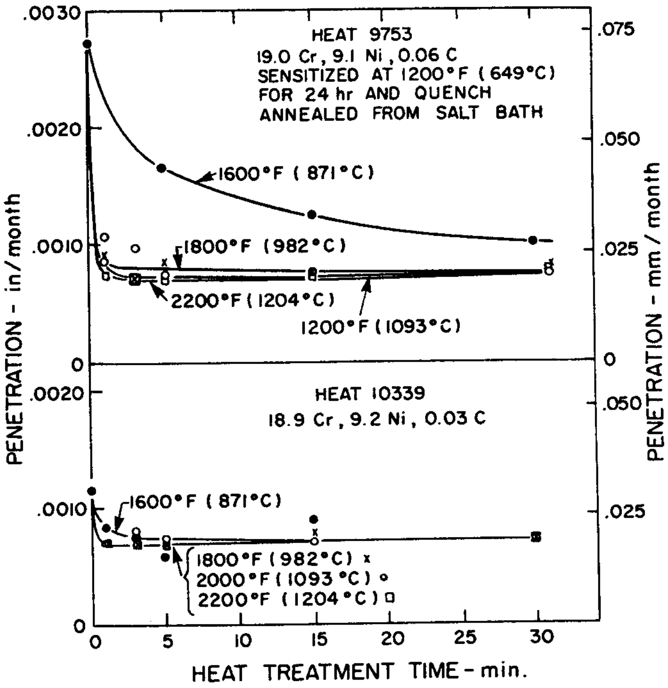

Fig. 55 Corrosion rates in nitric acid of 19 Cr-9 Ni stainless steel containing 0.12% carbon after heat treatment at 1600 to 2200°F (871 to 1204°C) for 1 to 30 minutes.

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