hardening. Similarly, for wrought products, normalization can help reduce banded grain structure due to hot rolling, as well as large grain size or mixed large and small grain size due to forging practice.

Heating and Cooling

For normalizing, austenitizing is carried out in a temperature range slightly higher than that normally used for hardening for water quenching, to ensure a homogeneous austenite. Typically, the work is heated to a temperature approximately 55 °C (100 °F) above the upper critical line of the iron-iron carbide phase diagram, as shown in Fig. 4; that is, above Ac_3 for hypoeutectoid steels and above A_{cm} for hypereutectoid steels. To be properly classed as a normalizing treatment, the heating portion of the process must produce a homogeneous austenitic phase prior to cooling. Figure 5 compares the time-temperature cycle of normalizing to that of full annealing. Typical normalizing temperatures for many standard steels are given in Table 1.

Uniform cooling requires free circulation of air around each piece so that there is no area in which the cooling has been restricted or accelerated. Restriction of the cooling rate will alter the operation from a normalizing to an annealing treatment.

The cooling curves in Fig. 6 demonstrate the effect of mass and section size on cooling in still air for carbon steel bars ranging from 100 to 270 mm (4 to 10½ in.) in diameter. A summary of cooling curves at the bar center is in Fig. 7. Cooling curves on a logarithmic scale are plotted in Fig. 8.

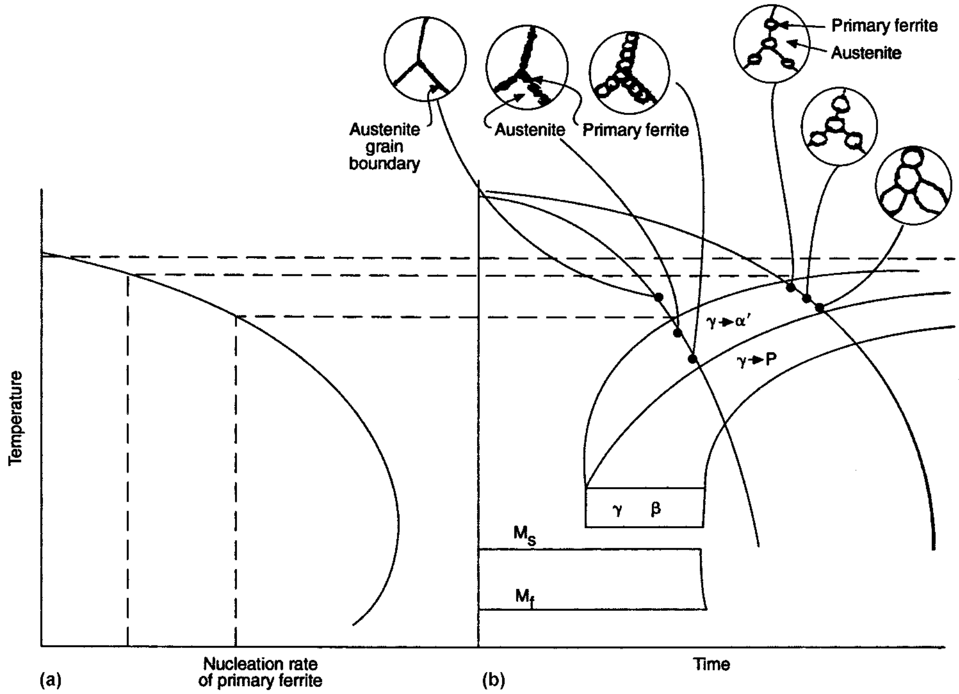

Fig. 2 Effect of normalizing process on primary ferrite formation. (a) Effect of temperature on the nucleation rate of primary ferrite at the grain boundaries of austenite. (b) Effect of cooling rate from austenite on the grain size of the primary ferrite crystals. Source: Ref 1

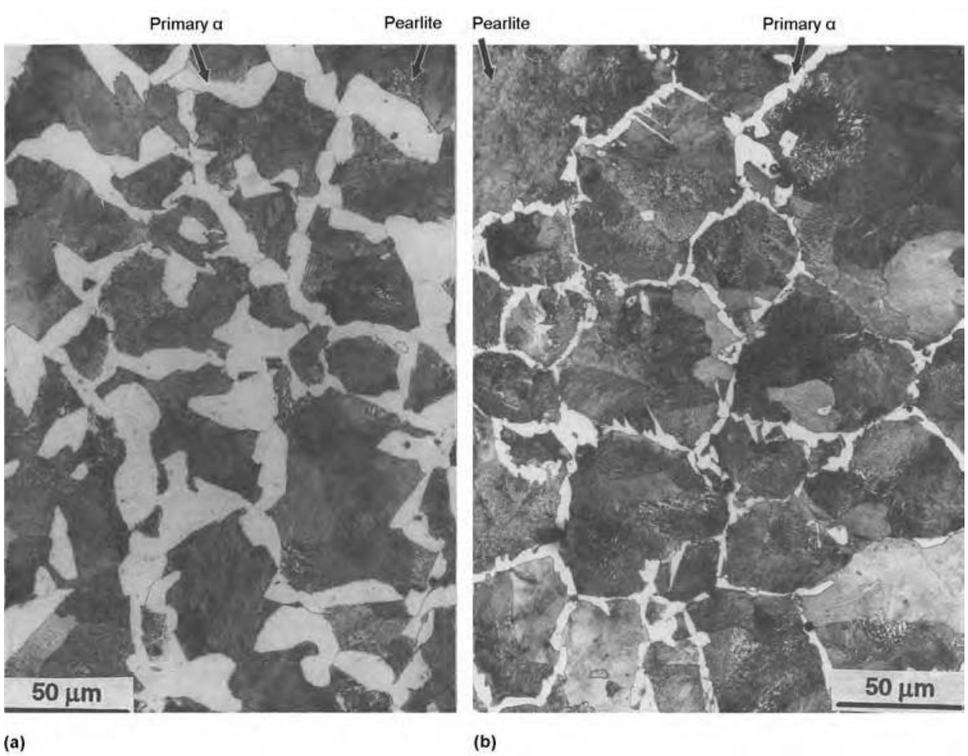

Fig. 3 Extent and finer structure of pearlite in a 0.5% C plain carbon steel from (a) furnace cooling (annealing) and (b) air cooling (normalizing). Source: Ref 1

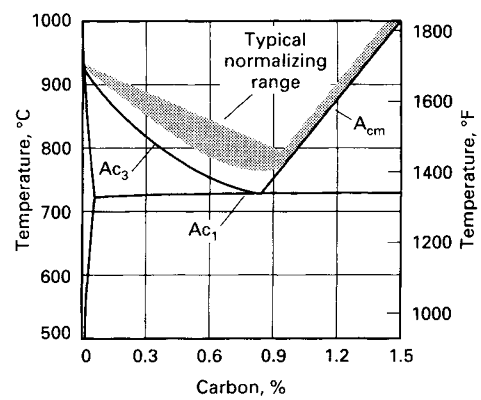

Fig. 4 Partial iron-iron carbide phase diagram showing typical normalizing range for plain carbon steels

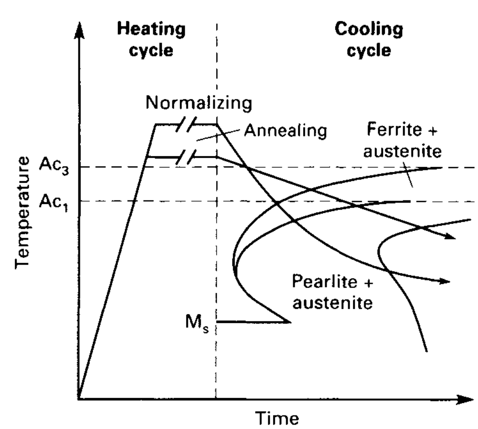

Fig. 5 Comparison of time-temperature cycles for normalizing and full annealing. The slower cooling of annealing results in higher temperature transformation to ferrite and pearlite and coarser microstructures than does normalizing. Source: Ref 2

Table 1 Typical normalizing temperatures for standard carbon and alloy steels

Grade	Temperature(a) °C	Temperature(a) °F
Plain carbon steels		
1015	915	1675
1020	915	1675
1022	915	1675
1025	900	1650
1030	900	1650
1035	885	1625
1040	860	1575
1045	860	1575
1050	860	1575
1060	830	1525
1080	830	1525
1090	830	1525
1095	845	1550
1117	900	1650
1137	885	1625
1141	860	1575
1144	860	1575
Standard alloy steels		
1330	900	1650
1335	870	1600
1340	870	1600
3135	870	1600
3140	870	1600
3310	925	1700
4027	900	1650
4028	900	1650
4032	900	1650
4037	870	1600
4042	870	1600
4047	870	1600
4063	870	1600
4118	925	1700
4130	900	1650
4135	870	1600
4137	870	1600
4140	870	1600
4142	870	1600
4145	870	1600
4147	870	1600
4150	870	1600
4320	925	1700
4337	870	1600
4340	870	1600
4520	925	1700
4620	925	1700
4621	925	1700
4718	925	1700
4720	925	1700
4815	925	1700
4817	925	1700
4820	925	1700
5046	870	1600
5120	925	1700
5130	900	1650
5132	900	1650
5135	870	1600
5140	870	1600
5145	870	1600
5147	870	1600
5150	870	1600
5155	870	1600
5160	870	1600
6118	925	1700
6120	925	1700
6150	900	1650
8617	925	1700
8620	925	1700
8622	925	1700
8625	900	1650
8627	900	1650
8630	900	1650
8637	870	1600
8640	870	1600
8642	870	1600
8645	870	1600
8650	870	1600
8655	870	1600
8660	870	1600
8720	925	1700
8740	925	1700
8742	870	1600
8822	925	1700
9255	900	1650
9260	900	1650
9262	900	1650
9310	925	1700
9840	870	1600
9850	870	1600
50B40	870	1600
50B44	870	1600
50B46	870	1600
50B50	870	1600
60B60	870	1600
81B45	870	1600
86B45	870	1600
94B15	925	1700
94B17	925	1700
94B30	900	1650
94B40	900	1650

(a) Based on production experience, normalizing temperature may vary from as much as 27 °C (50 °F) below to as much as 55 °C (100 °F) above indicated temperature. The steel should be cooled in still air from indicated temperature.

Applications of Normalizing Based on Steel Classification

A broad range of ferrous products can be normalized. Normalizing may harden, soften, or stress relieve, depending on the condition of the product before normalizing. All of the standard low-, medium-, and high-carbon wrought steels can be normalized, as well as many castings. Many steel weldments are normalized to refine the structure within the weld-affected area. Austenitic steels, stainless steels, and maraging steels either cannot be normalized or are not usually normalized. Tool steels are generally annealed by the steel supplier.

The details of normalizing treatments applied to three typical production parts are given in Table 2, which also lists the reasons for normalizing and gives some of the mechanical properties obtained in the normalized and tempered condition. Comparisons of typical hot-rolled or annealed mechanical properties versus typical normalized properties are presented in Table 3.

Figure 9 shows that high-carbon steels with large amounts of pearlite have high transition temperatures and therefore will fail in a brittle manner even well above room temperature. On the other hand, low-carbon steels have subzero transition temperatures and are quite tough at room temperature (Ref 2).

Depending on the mechanical properties required, normalizing may be substituted for conventional hardening when the size or shape of the part is such that liquid quenching may result in cracking, distortion, or excessive dimensional changes. Thus, parts that are of complex shape or that incorporate sharp changes in section may be normalized and tempered, provided that the properties obtained are acceptable.

The rate of heating generally is not critical for normalizing; on an atomic scale, it is immaterial. In parts having great variations in section size, however, thermal stress can cause distortion.

Time at temperature is critical only in that it must be sufficient to cause homogenization. Sufficient time must be allowed for solution of thermodynamically stable carbides or for diffusion of constituent atoms. Generally, time sufficient for complete austenitization is all that is required. One hour at temperature, after the furnace recovers, per inch of part thickness, is considered to be standard. Parts often can be austenitized adequately in much less time (with a saving of energy). In cases where normalizing is done to homogenize segregated structures, longer times may be required.

The rate of cooling significantly influences both the amount of pearlite and the size and spacing of the pearlite lamellae. At higher cooling rates, more pearlite forms, and the lamellae are finer and more closely spaced. Both the increased amount of pearlite and the greater fineness of the pearlite result in higher strength and higher hardness. Conversely, lower cooling rates result in softer parts.

The effect of mass on hardness (via its effect on cooling rate) is illustrated by the data in Table 4. In any part having both thick and thin sections, the potential exists for variations in cooling rate and thus for variations in strength and hardness as well. This can also increase the probability of distortion or even cracking. Cooling rate sometimes is enhanced with fans to increase strength and hardness of parts or to decrease the time required, following the furnace operation, for sufficient cooling of parts to permit convenient handling.

After parts have cooled uniformly through their cross section to black heat below Ar_1 (the parts are no longer red, as when they were removed from the furnace), they may be water or oil quenched to decrease the total cooling time. In heavy sections, cooling of the center material to black heat may require considerable time. Thermal shock, residual thermally induced stress, and resultant distortions are factors to be considered. The microstructure remains essentially unaffected by the increased cooling rate, provided that the entire mass is below the lower critical temperature, Ar_1, although changes involving precipitates may occur.

Carbon Steels. Table 1 lists typical normalizing temperatures for some standard grades of carbon steel. These temperatures can be interpolated to obtain values for carbon contents not listed.

Steels containing 0.20% C or less usually receive no treatment subsequent to normalizing. However, medium- or high-carbon steels are often tempered after normalizing to obtain specific properties, such as a lower hardness for

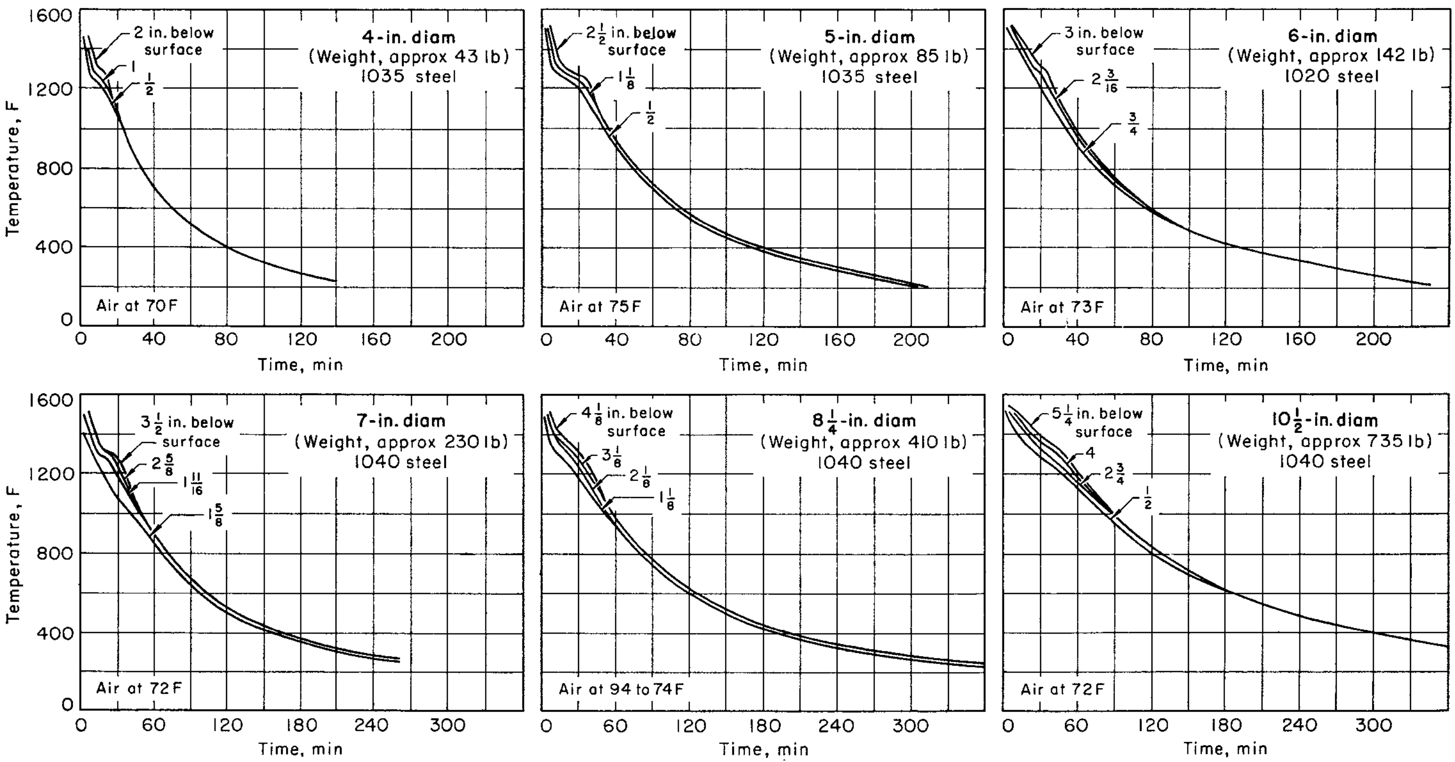

Fig. 6 Effect of mass and section on cooling curves in still air. Note the difference in the horizontal scales of the two rows.

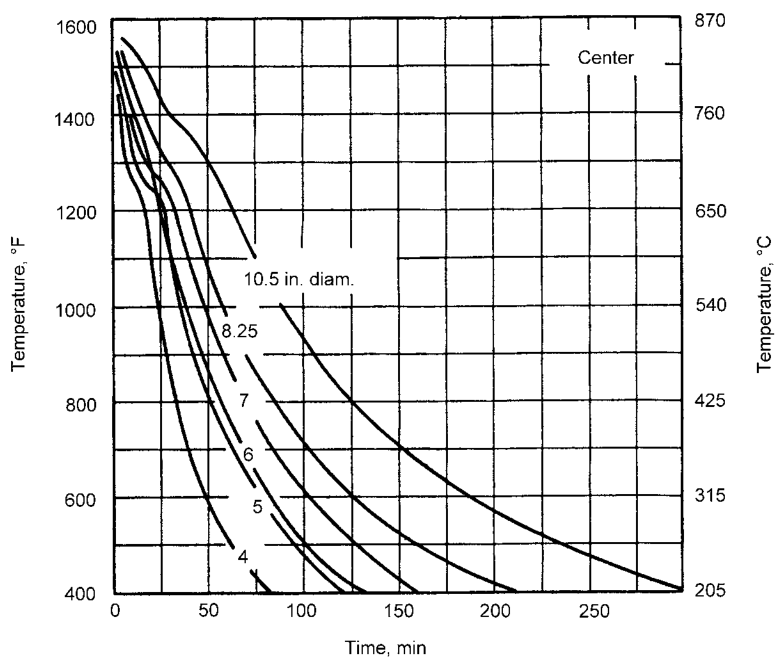

Fig. 7 Summary of center-cooling curves from Fig. 6

straightening, cold working, or machining. Whether tempering is desirable depends on specific property requirements and not on carbon content and section-size requirements. Table 3 presents typical mechanical properties of selected carbon and alloy steels in the hot-rolled, normalized, and annealed conditions. Because of pearlite lamellae and spacing, a low- or medium-carbon steel of thin section may be harder after normalizing than a high-carbon steel of large section size subjected to the same treatment.

Alloy Steels. For alloy steel forgings, rolled products, and castings, normalizing is commonly used as a conditioning treatment before final heat treatment. Normalizing also refines the structures of forgings, rolled products, and castings that have cooled nonuniformly from high temperatures. Table 1 lists typical normalizing temperatures for some standard alloy steels. Alloy carburizing steels such as 3310 and 4320 usually are normalized at temperatures higher than the carburizing temperature to minimize distortion in carburizing and to improve machining characteristics. Carburizing steels of the 3300 series sometimes are double normalized, with the expectation of minimizing distortion; these steels are tempered at approximately 650 °C (1200 °F) for intervals of up to 15 h to reduce hardness to below 223 HB for machinability. Carburizing steels of the 4300 and 4600 series usually can be normalized to a hardness not exceeding 207 HB and therefore need not be tempered for machinability.

Hypereutectoid alloy steels such as 52100 are normalized for partial or complete elimination of carbide networks, thus producing a structure that is more susceptible to 100% spheroidization in the subsequent spheroidize annealing treatment. The spheroidized structure provides improved machinability and a more uniform response to hardening.

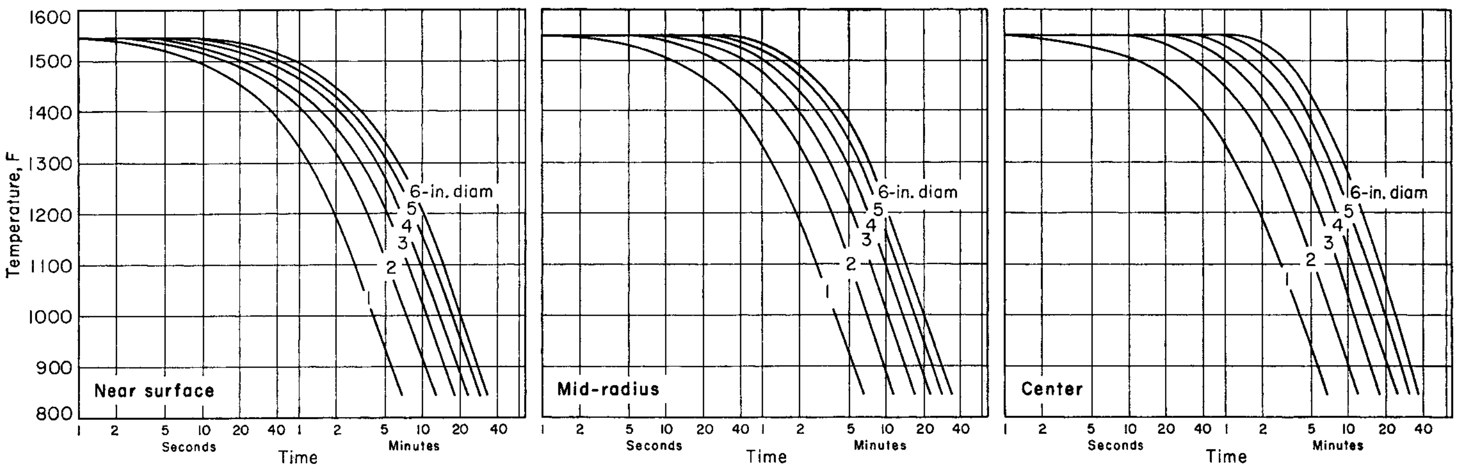

Fig. 8 Logarithmic time scale of cooling curves for steel bar of various diameters

Table 2 Typical applications of normalizing and tempering of steel components

Part	Steel	Heat treatment	Properties after treatment	Reason for normalizing
Cast 50 mm (2 in.) valve body, 19 to 25 mm (¾ to 1 in.) in section thickness	Ni-Cr-Mo	Full annealed at 955 °C (1750 °F), normalized at 870 °C (1600 °F), tempered at 665 °C (1225 °F)	Tensile strength, 620 MPa (90 ksi); 0.2% yield strength, 415 MPa (60 ksi); elongation in 50 mm, or 2 in., 20%; reduction in area, 40%	To meet mechanical-property requirements
Forged flange	4137	Normalized at 870 °C (1600 °F), tempered at 570 °C (1060 °F)	Hardness, 200 to 225 HB	To refine grain size and obtain required hardness
Valve-bonnet forging	4140	Normalized at 870 °C (1600 °F) and tempered	Hardness, 220 to 240 HB	To obtain uniform structure, improved machinability, and required hardness

Some alloy grades require more care in heating to prevent cracking from thermal shock. They also require longer soaking times because of lower austenitizing and solution rates. For many alloy steels, rates of cooling in air to room temperature must be carefully controlled. Certain alloy steels are forced-air cooled from the normalizing temperature in order to develop specific mechanical properties.

Forgings

When forgings are normalized before carburizing or before hardening and tempering, the upper range of normalizing temperatures is used. However, when normalizing is the final heat treatment, use is made of the lower range of temperatures.

Furnaces. Any appropriately sized furnace may be used for normalizing. Furnace type and size will depend upon the specific need. In a continuous furnace, forgings to be normalized are usually placed in shallow pans, and a pusher mechanism at the loading end of the furnace transports the pans through the furnace. Furnace burners located on both sides of the furnace fire below the hearth, and combustion products rise along the walls of the work-zone muffle and exhaust into the roof of the furnace. No atmosphere control is used. Combustion products enter the work zone through ports lining both sides of the entire hearth. A typical furnace is 9 m (30 ft) long and has 18 gas burners (or 9 oil burners) on each side. For purposes of temperature control, such a furnace is divided into three 3 m (10 ft) zones, each having a vertical thermocouple extending into it through the roof of the furnace.

Processing. Small forgings are usually normalized as received from the forge shop. A typical furnace has five pans in each of the three furnace zones. Heating is adjusted so that the work reaches normalizing temperature in the last zone. After passing through the last zone, the pans are discharged onto a cooling conveyor. The work, while still in the pans, is cooled in still air to below 480 °C (900 °F); it is then discharged into tote boxes, where it cools to room temperature. Total furnace time is approximately 3½ h, but during this period the work is held at the normalizing temperature for only 1 h.

Normalizing of large open-die forgings usually is performed in batch-type furnaces pyrometrically controlled to narrow temperature ranges. Forgings are held at the normalizing temperature long enough to allow complete austenitizing and carbide solution to occur (usually one hour per inch of section thickness) and then are cooled in still air.

Axle-Shaft Forging. In forging an axle shaft made of fine-grained 1049 steel, only one end of the forging bar was heated to upset the wheel-flange section. When the part was examined in cross section from the flanged end to the cold end, the metallurgical conditions discussed subsequently were revealed.

The hot-worked flanged area of the axle exhibited a fine-grained structure as a result of the hot working at the forging temperature (approximately 1095 °C, or 2000 °F). However, a section adjacent to the flange, which also had been heated to the forging temperature but which had not been hot worked, exhibited a coarse-grained structure. Nearer the cool end of the shaft, a zone that reached a temperature of approximately 705 °C (1300 °F) exhibited a spheroidized structure. The cold end of the shaft retained its initial fine grain size throughout the forging operation.

In subsequent operations, this shaft was to be mechanically straightened, machined, and induction hardened. Because of the mixed grain structure, these operations posed several problems. The coarse-grained area adjacent to the flange was extremely weak in the transverse direction, and there was a possibility that fracture would occur if this section were subjected to a severe straightening operation. The spheroidized area would not respond adequately to induction hardening because the solution rate of this type of carbide formation was too sluggish for the relatively rapid rate of induction heating. Furthermore, the mixed metallurgical structure would present difficulties in machining. Consequently, normalizing was required in order to produce a uniformly fine-grained structure throughout the axle shaft

Table 3 Properties of selected carbon and alloy steels in the hot-rolled, normalized, and annealed conditions

AISI grade(a)	Condition or treatment	Tensile strength		Yield strength		Elongation(b), %	Reduction in area, %	Hardness, HB	Izod impact strength	
		MPa	ksi	MPa	ksi				J	ft · lbf
1015	As-rolled	420	61	315	46	39.0	61	126	111	82
	Normalized at 925 °C (1700 °F)	425	62	325	47	37.0	70	121	115	85
	Annealed at 870 °C (1600 °F)	385	56	285	41	37.0	70	111	115	85
1020	As-rolled	450	65	330	48	36.0	59	143	87	64
	Normalized at 870 °C (1600 °F)	440	64	345	50	35.8	68	131	118	87
	Annealed at 870 °C (1600 °F)	395	57	295	43	36.5	66	111	123	91
1022	As-rolled	505	73	360	52	35.0	67	149	81	60
	Normalized at 925 °C (1700 °F)	485	70	360	52	34.0	68	143	117	87
	Annealed at 870 °C (1600 °F)	450	65	315	46	35.0	64	137	121	89
1030	As-rolled	550	80	345	50	32.0	57	179	75	55
	Normalized at 925 °C (1700 °F)	525	76	345	50	32.0	61	149	94	69
	Annealed at 845 °C (1550 °F)	460	67	345	50	31.2	58	126	69	51
1040	As-rolled	620	90	415	60	25.0	50	201	49	36
	Normalized at 900 °C (1650 °F)	595	86	370	54	28.0	55	170	65	48
	Annealed at 790 °C (1450 °F)	520	75	350	51	30.2	57	149	45	33
1050	As-rolled	725	105	415	60	20.0	40	229	31	23
	Normalized at 900 °C (1650 °F)	750	109	430	62	20.0	39	217	27	20
	Annealed at 790 °C (1450 °F)	635	92	365	53	23.7	40	187	18	13
1060	As-rolled	815	118	485	70	17.0	34	241	18	13
	Normalized at 900 °C (1650 °F)	775	113	420	61	18.0	37	229	14	10
	Annealed at 790 °C (1450 °F)	625	91	370	54	22.5	38	179	11	8
1080	As-rolled	965	140	585	85	12.0	17	293	7	5
	Normalized at 900 °C (1650 °F)	1015	147	525	76	11.0	21	293	7	5
	Annealed at 790 °C (1450 °F)	615	89	380	55	24.7	45	174	7	5
1095	As-rolled	965	140	570	83	9.0	18	293	4	3
	Normalized at 900 °C (1650 °F)	1015	147	505	73	9.5	14	293	5	4
	Annealed at 790 °C (1450 °F)	655	95	380	55	13.0	21	192	3	2
1117	As-rolled	490	71	305	44	33.0	63	143	81	60
	Normalized at 900 °C (1650 °F)	470	68	305	44	33.5	54	137	85	63
	Annealed at 860 °C (1575 °F)	430	62	285	41	32.8	58	121	94	69
1118	As-rolled	525	76	315	46	32.0	70	149	109	80
	Normalized at 925 °C (1700 °F)	475	69	315	46	33.5	66	143	103	76
	Annealed at 790 °C (1450 °F)	450	65	285	41	34.5	67	131	107	79
1137	As-rolled	625	91	380	55	28.0	61	192	83	61
	Normalized at 900 °C (1650 °F)	670	97	400	58	22.5	49	197	64	47
	Annealed at 790 °C (1450 °F)	585	85	345	50	26.8	54	174	50	37
1141	As-rolled	675	98	360	52	22.0	38	192	11	8
	Normalized at 900 °C (1650 °F)	710	103	405	59	22.7	56	201	53	39
	Annealed at 815 °C (1500 °F)	600	87	355	51	25.5	49	163	34	25
1144	As-rolled	705	102	420	61	21.0	41	212	53	39
	Normalized at 900 °C (1650 °F)	670	97	400	58	21.0	40	197	43	32
	Annealed at 790 °C (1450 °F)	585	85	345	50	24.8	41	167	65	48
1340	Normalized at 870 °C (1600 °F)	835	121	560	81	22.0	63	248	92	68
	Annealed at 800 °C (1475 °F)	705	102	435	63	25.5	57	207	71	52
3140	Normalized at 870 °C (1600 °F)	890	129	600	87	19.7	57	262	54	40
	Annealed at 815 °C (1500 °F)	690	100	420	61	24.5	51	197	46	34
4130	Normalized at 870 °C (1600 °F)	670	97	435	63	25.5	60	197	87	64
	Annealed at 865 °C (1585 °F)	560	81	360	52	28.2	56	156	62	46
4140	Normalized at 870 °C (1600 °F)	1020	148	655	95	17.7	47	302	23	17
	Annealed at 815 °C (1500 °F)	655	95	420	61	25.7	57	197	54	40
4150	Normalized at 870 °C (1600 °F)	1160	168	740	107	11.7	31	321	12	9
	Annealed at 815 °C (1500 °F)	730	106	380	55	20.2	40	197	24	18
4320	Normalized at 895 °C (1640 °F)	795	115	460	67	20.8	51	235	73	54
	Annealed at 850 °C (1560 °F)	580	84	430	62	29.0	58	163	110	81
4340	Normalized at 870 °C (1600 °F)	1280	186	860	125	12.2	36	363	16	12
	Annealed at 810 °C (1490 °F)	745	108	475	69	22.0	50	217	52	38
4620	Normalized at 900 °C (1650 °F)	570	83	365	53	29.0	67	174	135	98
	Annealed at 860 °C (1575 °F)	510	74	370	54	31.3	60	149	94	69
4820	Normalized at 860 °C (1580 °F)	760	110	485	70	24.0	59	229	110	81
	Annealed at 815 °C (1500 °F)	685	99	460	67	22.3	59	197	94	69
5140	Normalized at 870 °C (1600 °F)	795	115	475	69	22.7	59	229	38	28
	Annealed at 830 °C (1525 °F)	570	83	295	43	28.6	57	167	41	30
5150	Normalized at 870 °C (1600 °F)	870	126	530	77	20.7	59	255	31	23
	Annealed at 825 °C (1520 °F)	675	98	360	52	22.0	44	197	26	19
5160	Normalized at 860 °C (1575 °F)	960	139	530	77	17.5	45	269	11	8
	Annealed at 815 °C (1495 °F)	725	105	275	40	17.2	31	197	10	7
6150	Normalized at 870 °C (1600 °F)	940	136	615	89	21.8	61	269	35	26
	Annealed at 815 °C (1500 °F)	665	97	415	60	23.0	48	197	27	20
8620	Normalized at 910 °C (1675 °F)	635	92	360	52	26.3	60	183	100	74
	Annealed at 870 °C (1600 °F)	540	78	385	56	31.3	62	149	115	83
8630	Normalized at 870 °C (1600 °F)	650	94	430	62	23.5	54	187	95	70
	Annealed at 845 °C (1550 °F)	565	82	370	54	29.0	59	156	95	70
8650	Normalized at 870 °C (1600 °F)	1025	149	690	100	14.0	45	302	14	10
	Annealed at 795 °C (1465 °F)	715	104	385	56	22.5	46	212	30	22
8740	Normalized at 870 °C (1600 °F)	930	135	605	88	16.0	48	269	18	13
	Annealed at 815 °C (1500 °F)	695	101	415	60	22.2	46	201	41	30
9255	Normalized at 900 °C (1650 °F)	930	135	580	84	19.7	43	269	14	10
	Annealed at 845 °C (1550 °F)	775	112	490	71	21.7	41	229	10	7
9310	Normalized at 890 °C (1630 °F)	910	132	570	83	18.8	58	269	119	88
	Annealed at 845 °C (1550 °F)	820	119	440	64	17.3	42	241	79	58

(a) All grades are fine grained except for those

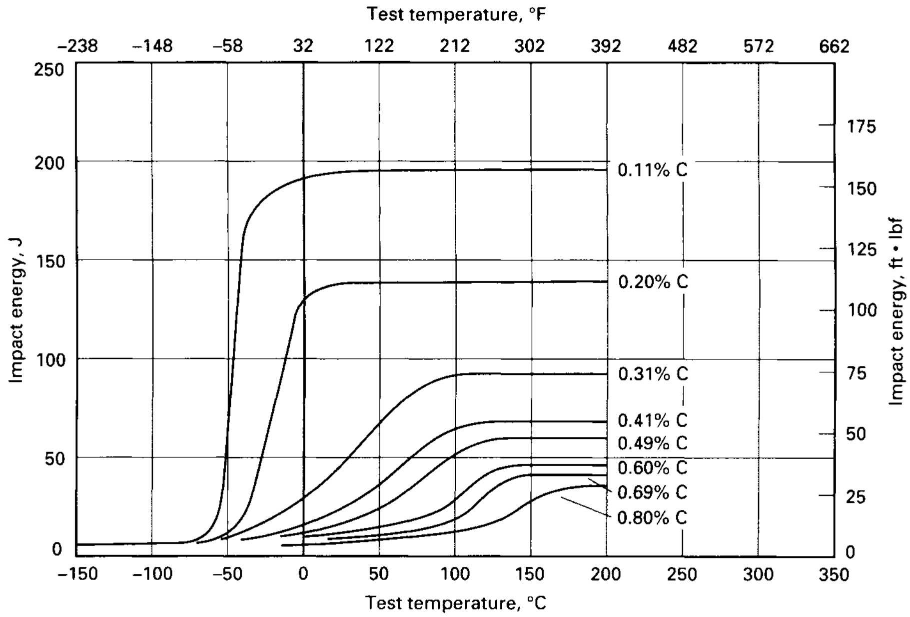

Fig. 9 Change in impact transition curves with increasing pearlite content in normalized carbon steels. Source: Ref 2

Table 4 Effect of mass on hardness of normalized carbon and alloy steels

	Normalizing temperature		Hardness, HB, for bar with diameter, mm (in.), of:			
Grade	°C	°F	13 (½)	25 (1)	50 (2)	100 (4)
Carbon steels, carburizing grades						
1015	925	1700	126	121	116	116
1020	925	1700	131	131	126	121
1022	925	1700	143	143	137	131
1117	900	1650	143	137	137	126
1118	925	1700	156	143	137	131
Carbon steels, direct-hardening grades						
1030	925	1700	156	149	137	137
1040	900	1650	183	170	167	167
1050	900	1650	223	217	212	201
1060	900	1650	229	229	223	223
1080	900	1650	293	293	285	269
1095	900	1650	302	293	269	255
1137	900	1650	201	197	197	192
1141	900	1650	207	201	201	201
1144	900	1650	201	197	192	192
Alloy steels, carburizing grades						
3310	890	1630	269	262	262	248
4118	910	1670	170	156	143	137
4320	895	1640	248	235	212	201
4419	955	1750	149	143	143	143
4620	900	1650	192	174	167	163
4820	860	1580	235	229	223	212
8620	915	1675	197	183	179	163
9310	890	1630	285	269	262	255
Alloy steels, direct-hardening grades						
1340	870	1600	269	248	235	235
3140	870	1600	302	262	248	241
4027	905	1660	179	179	163	156
4063	870	1600	285	285	285	277
4130	870	1600	217	197	167	163
4140	870	1600	302	302	285	241
4150	870	1600	375	321	311	293
4340	870	1600	388	363	341	321
5140	870	1600	235	229	223	217
5150	870	1600	262	255	248	241
5160	855	1575	285	269	262	255
6150	870	1600	285	269	262	255
8630	870	1600	201	187	187	187
8650	870	1600	363	302	293	285
8740	870	1600	269	269	262	255
9255	900	1650	277	269	269	269

Note: All data are based on single heats. Source: Ref 3, 4

prior to straightening, machining, and induction hardening.

Low-Carbon Steel Forgings. In contrast to the medium-carbon axle shaft discussed in the preceding paragraphs, forgings made of carbon steels containing 0.25% C or less are seldom normalized. Only severe quenching from above the austenitizing temperature will have any significant effect on their structure or hardness.

Structural Stability. Normalizing and tempering is also a preferred treatment for promoting the structural stability of low-alloy heat-resistant alloys, such as AMS 6304 (0.45% C, 1% Cr, 0.5% Mo, and 0.3% V), at temperatures up to 540 °C (1000 °F). Wheels and spacer rings used in the cold ends of aircraft gas-turbine engine compressors are typical of parts subjected to such treatment to promote structural stability.

Multiple normalizing treatments are employed to obtain complete solution of all lower-temperature constituents in austenite by the use of high initial normalizing temperatures (for example, 925 °C, or 1700 °F) and to refine final pearlite grain size by the use of a second normalizing treatment at a temperature closer to the Ac_3 temperature (for example, 815 °C, or 1500 °F) without destroying the beneficial effects of the initial normalizing treatment. Double normalizing is usually applied to carbon and low-alloy steels of large dimension where extremely high forging temperatures have been used (Ref 5). Locomotive-axle forgings made of carbon steel to Association of American Railroads Specification M-126, Class F (ASTM A236, Class F), containing 0.45 to 0.59% C and 0.60 to 0.90% Mn, are double normalized to obtain a uniformly fine grain structure along with other exacting mechanical-property requirements. Forgings made of a low-carbon steel (0.18% C) with 1% Mn intended for low- temperature service are double normalized to meet subzero impact requirements.

Bar and Tubular Products

Frequently, the finishing stages of hot-mill operations employed in making steel bar and tube produce properties that closely approximate those obtained by normalizing. When this occurs, normalizing is unnecessary and may even be inadvisable. Nevertheless, the reasons for normalizing bar and tube products are generally the same as those applicable to other forms of steel.

The machinability of steel bars and tubular products depends on a combination of hardness properties and microstructure. For a low-carbon alloy steel, a coarse pearlitic structure obtained by normalizing or annealing maximizes machinability. In the case of medium-carbon alloy steel, a lamellar pearlitic structure obtained by annealing is desirable in order to optimize machinability. For a high-carbon alloy steel, a spheroidized structure lowers the hardness and increases the machinability of the alloy. Prior processing, part configuration, and processing following machining should be taken into consideration when determining the need for annealing or normalization.

In general, annealing improves machinability more than normalization does. Normalizing is used to correct the effects of spheroidization, but the steel bar or tube still needs to be annealed. Multiple anneals and tempering are normally used on only small-diameter parts such as wire gage products. Type 4340 is one of the few steels that is typically delivered to the customer with a normalized heat treatment, due to machining specifications standard in the aircraft industry.

Tubes are easier to normalize than bars of equivalent diameter, because the lighter section thickness of tubes permits more rapid heating and cooling. These advantages help minimize decarburization and promote more nearly uniform microstructures in tube products.

Furnace Requirements. Continuous furnaces of the roller-hearth type are widely used for normalizing tube and bar products, especially in long lengths. Batch-type furnaces or other types of continuous furnaces are satisfactory if they provide some means for rapid discharge and separation of the load to permit free circulation of air around each tube as it cools. Continuous furnaces should have at least two zones: one for heating and one for soaking. Cooling facilities should be ample so that uniform cooling can proceed until complete transformation has occurred. If tubes are packed or bundled during cooling from a high temperature, the purpose of normalizing is defeated, and a semiannealed or a tempered product results.

Generally, protective atmospheres are not used in roller-hearth continuous furnaces for normalizing bar or tube products. The scale that forms during normalizing is removed by acid pickling or abrasive blast cleaning.

Castings

In industrial practice, steel castings may be normalized in car-bottom, box, pit, or continuous furnaces. The same heat treating principles apply to each type of furnace. The effect of normalizing on hardness and toughness is compared with annealing and quench-temper treatments in Fig. 10 and 11, respectively.

Furnace Loading. Furnaces are loaded with castings in such a manner that each casting will receive an adequate and uniform heat supply. This may be accomplished by stacking castings in regular order or by interspersing large and small castings so that load concentration in any one area is not excessive. At normalizing temperatures, the tensile strength of steel is greatly reduced, and heavy unequal sections may become distorted unless bracing and support are provided. Accordingly, small and large castings may be arranged so that they support each other.

Loading Temperature. When castings are charged, the temperature of the furnace should be such that the thermal shock will not cause metal failure. For the higher-alloy grades of steel castings, such as C5, C12, and WC9, a safe furnace temperature for charging is 315 to 425 °C (600 to 800 °F). For lower-alloy grades, furnace temperatures may be as high as 650 °C (1200 °F). For cast carbon steels and low-alloy steels with low carbon contents (low hardenability), castings may be charged into a furnace operating at the normalizing temperature.

Heating. After the furnace has been charged, the temperature is increased at a rate of approximately 225 °C/h (400 °F/h) until the normalizing temperature is reached. Depending on steel composition and casting configuration, a reduction in the rate of heating to approximately 28 to 55 °C/h (50 to 100 °F/h) may be necessary to avoid cracking. Extremely large castings should be heated more slowly to prevent development of extreme temperature gradients.

Soaking. After the normalizing temperature has been reached, castings are soaked at this temperature for a period that will ensure complete austenitization and carbide solution. The duration of the soaking period may be predetermined by microscopic examination of specimens held for various times at the normalizing temperature.

Cooling. After the soaking period, the castings are unloaded and allowed to cool in still air. Use of fans, air blasts, or other means of accelerating the cooling process should be avoided.

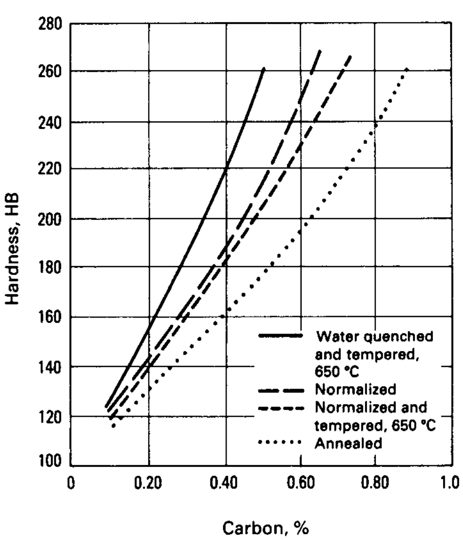

Fig. 10 Brinell hardness of cast carbon steels as a function of carbon content and heat treatment. Source: Ref 6

Sheet and Strip

Hot-rolled steel sheet and strip (approximately 0.10% C) are normalized primarily to refine grain size, to minimize directional properties, and to develop desirable mechanical properties. Uniformly fine equiaxed ferrite grains are normally obtained in hot-rolled sheet and strip by finishing the final hot-rolling operation above the upper transformation temperature. However, if part of the hot-rolling operation is performed on steel that has transformed partially to ferrite, the deformed ferrite grains usually will recrystallize and form abnormally coarse-grained patches during the self-anneal induced by coiling or piling at temperatures of 650 to 730 °C (1200 to 1350 °F). Also, relatively thin hot-rolled material, if it is inadvertently finished well below the upper transformation temperature and coiled or piled while it is too cold to self-anneal, may possess directional properties. These conditions are unsuitable for some types of severe press-drawing applications and may be corrected by normalizing.

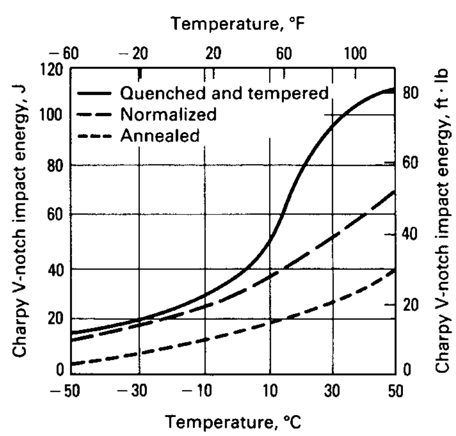

Fig. 11 Effect of various heat treatments on the Charpy V-notch impact energy of a 0.30% C steel. Source: Ref 6

Normalizing also may be used to develop high strength in alloy steel sheet and strip if the products are sufficiently high in carbon and alloy contents to enable them to transform to fine pearlite or martensite when cooled in air from the normalizing temperature. In general, the hardened material is tempered to attain an optimum combination of strength and ductility. Typical mechanical properties of normalized 4130, modified 4335, and modified 4340 steel sheet are given in Table 5.

Processing. The normalizing operation consists of passing the sheet or strip through an open, continuous furnace where the material is heated to a temperature approximately 55 to 85 °C (100 to 150 °F) above its upper transformation temperature, 845 to 900 °C (1550 to 1650 °F), thus obtaining complete solution of the original structure with the formation of austenite and then air cooling the material to room temperature.

Furnace Equipment. Normalizing furnaces are designed to heat and cool sheets singly or two in a pile. They are built in the form of long, low chambers and usually comprise three sections: a preheating zone (12 to 20% of the total length); a heating, or soaking, zone (approximately 40% of the total length); and a cooling zone, which occupies the remaining 40 to 50% of the length.

Heating Arrangements. Normalizing furnaces usually are heated with gas or oil and do not employ protective atmospheres. Therefore, sheets are scaled during heat treatment. Burners are arranged along each side of the heating zone; they usually are above the conveyor but occasionally are both above and below it. The furnace roof, which is higher in the preheating and soaking zones than in the cooling zone, is usually built in sections. In most furnaces, both the preheating zone and the cooling zone are heated by the hot gases from the heating zone. However, both of these zones may be equipped with burners for more accurate temperature control. Air is excluded by regulating the draft to maintain a slight pressure within all zones.

Conveyor-Type Furnaces. In modern furnaces of the conveyor type (the only type suitable for treating short lengths), sheets are carried through each of the three zones on rotating disks made of heat-resistant alloys. These disks have polished surfaces, which prevent

Table 5 Typical mechanical properties of normalized alloy steel sheet

Grade	Thickness		Tensile strength		Yield strength(a)		Elongation(b), %	Hardness, HRC
	mm	in.	MPa	ksi	MPa	ksi		
4130	4.9	0.193	835	121	585	85	14	25
4335(c)	4.6	0.180	1725	250	1240	180	8	48
4340(c)	2.0	0.080	1860	270	1345	195	7	50

(a) At 0.2% offset. (b) In 50 mm (2 in.). (c) Modified: 0.40% Mo, 0.20% V

them from scratching the sheets, and are staggered to ensure uniform heating. The disks are mounted on water-cooled shafts, which are driven by variable-speed motors through chains and sprockets or shafts and gears. These furnaces may be up to 2.5 m (100 in.) wide and from 27 to 61 m (90 to 200 ft) long. Fuel consumption is 2.3 to 5.2 $\times$ 10^6 kJ/tonne (2.0 to 4.5 $\times$ 10^6 Btu/ton) of steel treated, and production rates vary from 2.7 to 10.9 tonnes (3 to 12 tons) per hour.

Normalizing in a three-zone conveyor-type furnace equipped with pyrometric controls is a relatively simple operation. If scratching of sheets is to be avoided, the sheets are brought to the charging table and hand laid, one or more at a time, on a rider or conveyor sheet. Heavy sheets are normalized singly, but lighter sheets may be stacked two in a pile. To control heating and retard scaling, single sheets may be laid on a rider sheet and covered with a cover sheet. Sheets are carried by disk-rollers into the preheating zone, where they absorb heat rapidly because of the large temperature differential between the sheets and the interior of the furnace and because of the large surface-to-volume ratio. As the sheets become heated and the temperature differential is reduced, the rate of heat absorption slackens. After traveling 4½ to 6 m (15 to 20 ft), the sheets enter the soaking zone at a temperature several degrees below the normalizing temperature. Heating is completed in the soaking zone, which is maintained at a constant temperature, and sheets are held at the required temperature for a time sufficient to convert the microstructure to austenite before they are passed into the cooling zone. The sheets emerge from the cooling zone at a temperature that can be varied between 150 and 540 °C (300 and 1000 °F) and are conveyed for a short distance on the runout table, where, after being cooled rapidly in air, they are carefully removed from the rider sheet. The trip through such a furnace is carried out at a uniform speed of 0.03 to 0.10 m/s (5 to 20 ft/min) and requires 5 to 20 min to complete.

Catenary Furnaces. The catenary, or free-loop, type of furnace is designed for continuous normalizing of cold-reduced steel unwound from coils; it does not have rolls or any other type of conveyor for supporting the material passing through the heating zone. The heating zones of catenary furnaces range in length from 6 to 15 m (20 to 50 ft). The preheating and cooling zones usually are shorter than those in conveyor-type furnaces and, for some kinds of work, may be omitted entirely. At their exit ends, catenary furnaces may incorporate pickling or other descaling equipment for removing surface oxides formed on the steel during normalizing.

ACKNOWLEDGMENTS

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Annealing of Steel*

Revised by Satyam S. Sahay, John Deere Asia Technology Innovation Center, Pune, India

ANNEALING is a generic term denoting a treatment that consists of heating to and holding at a suitable temperature followed by cooling at an appropriate rate, primarily for the softening of metallic materials. Generally, annealing is done by heating in furnaces, although at times, annealing by induction heating is also done when rapid heating is an effective method (such as annealing of wire after drawing).

Metallurgical Principles

Generally, in plain carbon steels, annealing produces a ferrite-pearlite microstructure (Fig. 1). Steels may be annealed to facilitate cold working or machining, to improve mechanical or electrical properties, or to promote dimensional stability.

The iron-carbon binary phase diagram (Fig. 2) can be used to better understand annealing processes (Ref 1). Although no annealing process ever achieves true equilibrium conditions, it can closely parallel these conditions. In defining the various types of annealing, the transformation temperatures or critical temperatures are usually used.

Critical Temperatures. The critical temperatures define the onset and completion of the transformation to or from austenite. The equilibrium critical temperatures depicted on the binary iron-carbon phase diagram (Fig. 2) are A_1 and A_3 for hypoeutectoid steel and A_1 and A_{cm} for the hypereutectoid steel (Ref 1). It must be noted that due to the nonequilibrium effect, the critical cooling temperatures Ar_1, Ar_3, and Ar_{cm} (denoted with a suffix "r" for the French word *refroidissement* meaning cooling) are lower, whereas the critical heating temperatures Ac_1, Ac_3, and Ac_{cm} (denoted with a suffix "c" for the French word *chauffage*) are higher than the corresponding equilibrium temperatures. Various alloying elements markedly affect these critical temperatures. For example,

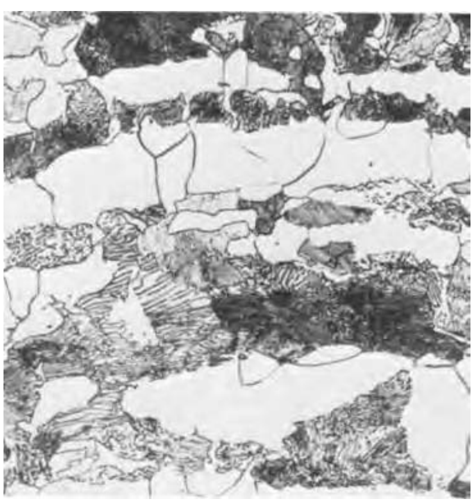

Fig. 1 Fully annealed 1040 steel showing a ferrite-pearlite microstructure. Etched in 4% picral plus 2% nital. Original magnification: 500×

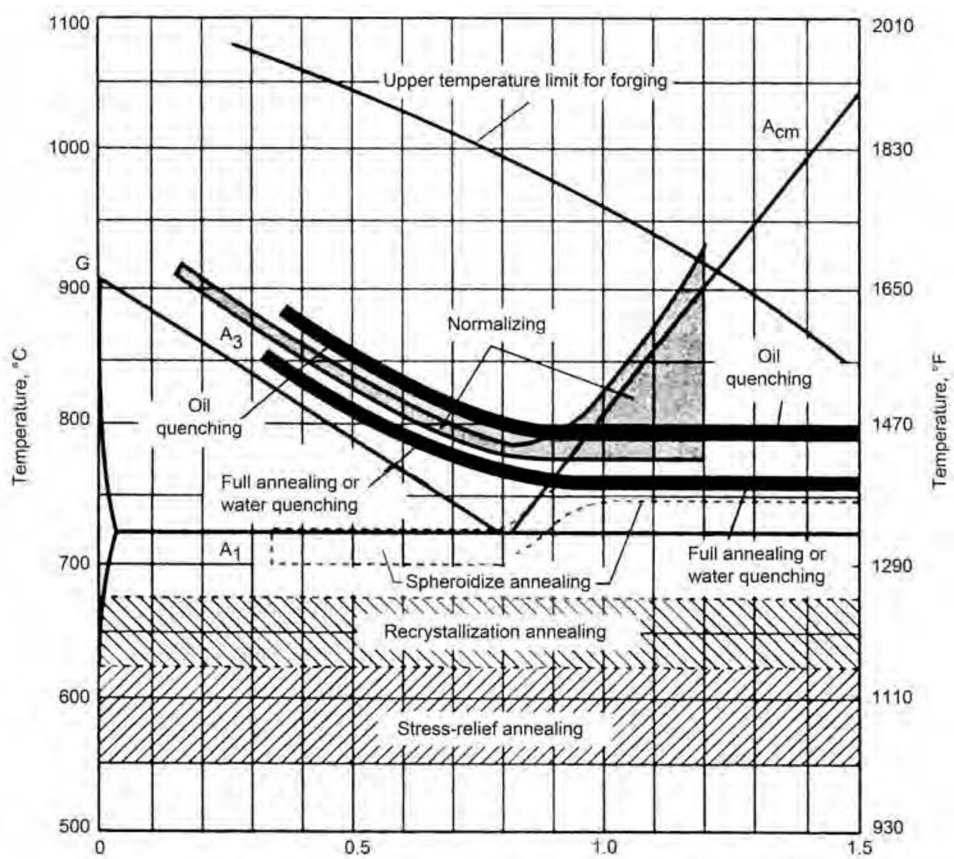

Fig. 2 Iron-carbon binary phase diagram with superimposed full annealing, process annealing, and spheroidizing treatments. Source: Ref 1

* Updated from Annealing of Steel and Continuous Annealing of Steel, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 42–66

chromium raises the eutectoid temperature, A_1, and manganese lowers it. The upper and lower critical temperatures can be calculated using the actual chemical composition of the steel (Ref 2).

Annealing Cycles

In practice, annealing cycles are classified based on the specific purpose and the temperature to which the steel is heated and the method of cooling used. The maximum temperature may be below the lower critical temperature, A_1 (subcritical annealing); above A_1 but below the upper critical temperature, A_3 in hypoeutectoid steels, or A_{cm} in hypereutectoid steels (intercritical annealing); or above A_3 (full annealing), which has been illustrated in Fig. 2.

Because some austenite is present at temperatures above A_1, cooling practice through transformation is a crucial factor in achieving desired microstructure and properties. Accordingly, steels heated above A_1 are subjected either to slow continuous cooling or to isothermal treatment at some temperature below A_1 at which transformation to the desired microstructure can occur in a reasonable amount of time. Under certain conditions, two or more such cycles may be combined or used in succession to achieve the desired results. The success of any annealing operation depends on the proper choice and control of the thermal cycle, based on the metallurgical principles discussed in the following sections.

Subcritical Annealing

Subcritical annealing does not involve formation of austenite. The prior condition of the steel is modified by such thermally activated processes as recovery, recrystallization, grain growth, and agglomeration of carbides. The prior history of the steel is therefore an important factor.

In as-rolled or forged hypoeutectoid steels containing ferrite and pearlite, subcritical annealing can adjust the hardnesses of both constituents, but excessively long times at temperature may be required for substantial softening. The subcritical treatment is most effective when applied to hardened or cold-worked steels, which recrystallize readily to form new ferrite grains. The rate of softening increases rapidly as the annealing temperature approaches A_1. Cooling practice from the subcritical annealing temperature has very little effect on the established microstructure and resultant properties. A more detailed discussion of the metallurgical processes involved in subcritical annealing is provided in Ref 3.

Intercritical Annealing

Austenite begins to form when the temperature of the steel exceeds A_1. The solubility of carbon increases abruptly (nearly 1%) near the A_1 temperature. In hypoeutectoid steels, the equilibrium structure in the intercritical range between A_1 and A_3 consists of ferrite and austenite, and above A_3 the structure becomes completely austenitic. However, the equilibrium mixture of ferrite and austenite is not achieved instantaneously. For example, the rate of solution for a typical eutectoid steel is shown in Fig. 3. Undissolved carbides may persist, especially if the austenitizing time is short or the temperature is near A_1, causing the austenite to be inhomogeneous. In hypereutectoid steels, carbide and austenite coexist in the intercritical range between A_1 and A_{cm}; and the homogeneity of the austenite depends on time and temperature. The degree of homogeneity in the structure at the austenitizing temperature is an important consideration in the development of annealed structures and properties. The more homogeneous structures developed at higher austenitizing temperatures tend to promote lamellar carbide structures on cooling, whereas lower austenitizing temperatures in the intercritical range result in less homogeneous austenite, which promotes formation of spheroidal carbides.

Austenite formed when steel is heated above the A_1 temperature transforms back to ferrite and carbide when the steel is slowly cooled below A_1. The rate of austenite decomposition and the tendency of the carbide structure to be either lamellar or spheroidal depend largely on the temperature of transformation. If the austenite transforms just below A_1, it will decompose slowly. The product then may contain relatively coarse spheroidal carbides or coarse lamellar pearlite, depending on the composition of the steel and the austenitizing temperature. This product tends to be very soft. However, the low rate of transformation at temperatures just below A_1 necessitates long holding times in isothermal treatments, or very slow cooling rates in continuous cooling, if maximum softness is desired. Isothermal treatments are more efficient than slow continuous cooling in terms of achieving desired structures and softness in the minimum amount of time. Sometimes, however, the available equipment or the mass of the steel part being annealed may make slow continuous cooling the only feasible alternative.

As the transformation temperature decreases, austenite generally decomposes more rapidly, and the transformation product is harder, more lamellar, and less coarse than the product formed just below A_1. At still lower transformation temperatures, the product becomes a much harder mixture of ferrite and carbide, and the time necessary for complete isothermal transformation may again increase.

Temperature-time plots showing the progress of austenite transformation under isothermal (IT) or continuous transformation (CT) conditions for many steels have been widely published (Ref 4, 5) and illustrate the principles just discussed. These IT or CT diagrams may be helpful in design of annealing treatments for specific grades of steel, but their usefulness is limited because most published diagrams represent transformation from a fully austenitized, relatively homogeneous condition, which is not always desirable or obtainable in annealing.

In the continuous annealing process, the intercritical annealing is leveraged to develop

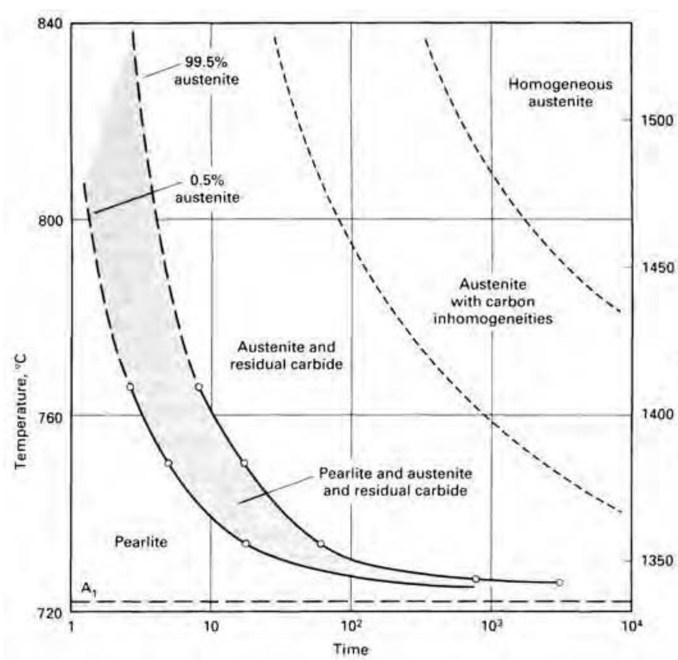

Fig. 3 Austenitizing rate-temperature curves for commercial plain carbon eutectoid steel. Prior treatment was normalizing from 875 °C (1610 °F); initial structure, fine pearlite. First curve at left shows beginning of disappearance of pearlite; second curve, final disappearance of pearlite; third curve, final disappearance of carbide; fourth curve, final disappearance of carbon concentration gradients.

dual-phase and tri-phase microstructures, with final microstructure consisting of islands of martensite in a ferritic matrix. Depending on the alloy content of the austenite pools and the cooling conditions, the austenite may not fully transform, and the microstructure will consist of martensite/retained austenite regions in a ferritic matrix.

Cooling after Transformation. After the austenite has been completely transformed, little else of metallurgical consequence can occur during cooling to room temperature. Extremely slow cooling may cause some agglomeration of carbides and, consequently, some slight further softening of the steel, but in this regard such slow cooling is less effective than high-temperature transformation. Therefore, there is no metallurgical reason for slow cooling after transformation has been completed, and the steel may be cooled from the transformation temperature as rapidly as feasible to minimize the total time required for the operation.

If transformation by slow continuous cooling has been used, the temperature at which controlled cooling may be stopped depends on the transformation characteristics of the steel. However, the mass of the steel or the need to avoid oxidation are practical considerations that may require retarded cooling to be continued below the temperature at which the austenite transformation ceases.

Effect of Prior Structure. The finer and more evenly distributed the carbides in the prior structure, the faster the rate at which austenite formed above A_1 will approach complete homogeneity. Therefore, the prior structure can affect the response to annealing. When spheroidal carbides are desired in the annealed structure, preheating at temperatures just below A_1 sometimes is used to agglomerate the prior carbides in order to increase their resistance to solution in the austenite on subsequent heating. The presence of undissolved carbides or concentration gradients in the austenite promotes formation of a spheroidal, rather than lamellar, structure when the austenite is transformed. Preheating to enhance spheroidization is applicable mainly to hypoeutectoid steels but also is useful for some hypereutectoid low-alloy steels.

Supercritical or Full Annealing

A common annealing practice is to heat hypoeutectoid steels above the upper critical temperature (A_3) to attain full austenitization. The process is called full annealing. In hypoeutectoid steels (under 0.77% C), supercritical annealing (that is, above the A_3 temperature) takes place in the austenite region (the steel is fully austenitic at the annealing temperature). However, in hypereutectoid steels (above 0.77% C), the annealing takes place above the A_1 temperature, which is the dual-phase austenite-cementite region. Figure 2 shows the annealing temperature range for full annealing superimposed in the iron-carbon binary phase diagram. In general, an annealing temperature 50 °C (90 °F) above the A_3 for hypoeutectic steels and A_1 for hypereutectoid steels is adequate.

Austenitizing Time and Dead-Soft Steel. Hypereutectoid steels can be made extremely soft by holding for long periods of time at the austenitizing temperature. Although the time at the austenitizing temperature may have only a small effect on actual hardnesses (such as a change from 241 to 229 HB), its effect on machinability or cold-forming properties may be appreciable.

Long-term austenitizing is effective in hypereutectoid steels because it produces agglomeration of residual carbides in the austenite. Coarser carbides promote a softer final product. In lower-carbon steels, carbides are unstable at temperatures above A_1 and tend to dissolve in the austenite, although the dissolution may be slow.

Steels that have approximately eutectoid carbon contents generally form a lamellar transformation product if austenitized for very long periods of time. Long-term holding at a temperature just above the A_1 temperature may be as effective in dissolving carbides and dissipating carbon-concentration gradients as is short-term holding at a higher temperature.

Guidelines for Annealing

The metallurgical principles discussed previously have been incorporated by Payson (Ref 6) into the following seven rules, which may be used as guidelines for development of successful and efficient annealing schedules:

- *Rule 1:* Fully homogeneous austenitized steel transforms to completely lamellar pearlitic structure after annealing, whereas heterogeneous austenitized steel transforms to nearly spheroidal annealed carbides.
- *Rule 2:* The softest condition in the steel is usually developed by austenitizing at a temperature less than 55 °C (100 °F) above A_1 and transforming at a temperature (usually) less than 55 °C (100 °F) below A_1.
- *Rule 3:* Because very long times may be required for complete transformation at temperatures less than 55 °C (100 °F) below A_1, allow most of the transformation to take place at the higher temperature, where a soft product is formed, and finish the transformation at a lower temperature, where the time required for completion of transformation is short.
- *Rule 4:* After the steel has been austenitized, cool to the transformation temperature as rapidly as feasible to minimize the total duration of the annealing operation.
- *Rule 5:* After the steel has been completely transformed, at a temperature that produces the desired microstructure and hardness, cool to room temperature as rapidly as feasible to decrease further the total time of annealing.
- *Rule 6:* To ensure a minimum of lamellar pearlite in the structures of annealed 0.70 to 0.90% C tool steels and other low-alloy medium-carbon steels, preheat for several hours at a temperature approximately 28 °C (50 °F) below the lower critical temperature (A_1) before austenitizing and transforming as usual.
- *Rule 7:* To obtain minimum hardness in annealed hypereutectoid alloy tool steels, heat at the austenitizing temperature for a long time (approximately 10 to 15 h), then transform as usual.

These rules are applied most effectively when the critical temperatures and transformation characteristics of the steel have been established and when transformation by isothermal treatment is feasible.

Annealing Temperatures

From a practical sense, most annealing practices have been established from experience. For many annealing applications, it is sufficient simply to specify that the steel be cooled in the furnace from a designated annealing (austenitizing) temperature. Temperatures and associated Brinell hardnesses for simple annealing of carbon steels are given in Table 1, and similar data for alloy steels are presented in Table 2.

Heating cycles that employ austenitizing temperatures in the upper ends of the ranges given in Table 2 should result in pearlitic structures. Predominantly spheroidized structures should be obtained when lower temperatures are used.

When an alloy steel is annealed to obtain a specific microstructure, greater precision is required in specifying temperatures and cooling conditions for annealing. Table 3 presents, for a variety of standard alloy steels, typical schedules for such annealing operations.

In isothermal annealing to produce a pearlitic structure, particularly in forgings, an austenitizing temperature as much as 70 °C (125 °F) higher than that indicated in Table 3 may be selected in order to decrease the austenitizing time.

For most steels, as indicated in Table 3, annealing may be accomplished by heating to the austenitizing temperature and then either cooling in the furnace at a controlled rate or cooling rapidly to, and holding at, a lower temperature for isothermal transformation. Both procedures result in virtually the same hardness; however, considerably less time is required for isothermal transformation.

Spheroidizing

The majority of all spheroidizing activity is performed for improving the cold formability