Fig. 29 shows a similar steel annealed at 900° for one and one-half hours and cooled in air, then reheated to 700° for one hour and cooled slowly; and Fig. 30, a steel heated to 900° for two hours and cooled in air, then reheated to 750° for one hour and cooled slowly. Comparing Fig. 29 with Fig. 26, we see that the structure of the air-cooled steel has been little if at all altered by the reheating to 700°, a temperature which brought out coarse ferrite in the quenched steel. In Fig. 30, however, there is an agglomeration of ferrite over the whole background, and also a well-defined agglomeration of ferrite into a large net-work.

These microphotographs have been selected from some hundreds which were made in the course of an extended research into the behavior of cast steel in heat treatment, and are typical examples. No hypo-eutectoid carbon cast steel tested in this research, and none yet brought to the author's attention, has failed to behave in the characteristic manner shown by these photographs. To be sure, the tendency to the formation of coarse ferrite showing traces of the net-work arrangement is not equally marked in all cast steels, yet none are wholly free from it. The predominance of a Widmanstättian arrangement of primary ferrite in the raw steel appears to decrease or mask the formation of this coarse net-work after annealing; and the presence of many slag or sulphide inclusions (usually associated with a strongly marked net-work structure in the raw steel), to increase it.

All electric furnace steels, however low in sulphur and phosphorus, that have come under the author's attention, show this same tendency to the retention of coarse ferrite patches after annealing; some more than others. Fig. 31, an electric furnace steel containing but .023 per cent. of sulphur and .017 per cent. of phosphorus, shows that even a steel very low in sulphur exhibits this tendency very strongly. The rather numerous inclusions in this specimen must be largely slag, which suggests that slag resists the advance of carbon into the ferrite as strongly as does sulphide of manganese, which would naturally be the case if the inclusions act as mechanical barriers to the progress of the diffusing particles; that slag as well as sulphide of manganese particles tend to hold the ferrite because it adheres to them; or that, as already suggested, the action of the inclusions is indirect, that is, that they act as nuclei upon which net-work austenite is deposited in freezing, and so favor the formation of coarse ferrite net-works, which are eliminated slowly by diffusion in annealing. This steel was annealed at 900° for four hours and cooled in air, then reheated to 760° for two hours and slowly cooled.

The well-marked coarse net-work is clearly shown, though it is less noticeable than in the previously exhibited examples, because, owing to the higher carbon (.59 per cent.), there is much less available free ferrite in this steel to form the coarse patches.

The great majority of steel castings requiring annealing are heated to about 900° and after soaking are slowly cooled, resulting in a structure similar to that of Fig. 25; coarser in larger castings, finer in smaller ones. In some cases, by opening the furnaces more or less and hastening the cooling, structures like Fig. 26 and Fig. 27 are obtained. The annealed steel will have a higher tensile strength, elastic limit, extension, contraction of area, and bend than the steel in the raw state; and by accelerated cooling the strength and elastic limit can be raised without sacrifice of toughness, or with actual gain of toughness; accelerated cooling, in particular, increases the resistance to sudden shock. The annealed castings will be softer than the raw steel—and, of course, quite free from shrinkage stresses, unless the accelerated cooling is continued until the castings are cold.

If accelerated cooling is used, the furnace should be closed up after the castings have reached black heat, and the cooling finished slowly enough to allow of the relief of cooling stresses. If the accelerated cooling has been very rapid, or if an air or water cooling has been used, the stresses set up in the castings will be nearly as great as in the raw state, and they must be heated a second time to relieve the stresses.

For convenience, the rates of cooling from the annealing temperature may be classified as follows:

1. Slow—over 50 minutes from 900° to black.
2. Accelerated { over 10 minutes from 900° to black. less than 50 minutes.
3. Rapid { less than 10 minutes from 900° to black, as for instance cooling in air or air blast.
4. Very rapid (quench in oil or water).

GENERAL RULES

General rules for the heat treatment of hypo-eutectoid carbon-steel castings may be given as follows:

Heat to 850 or 900° for from two to four hours after the castings are hot through.

The more rapid the cooling from the annealing temperature, the finer will be the microstructure, and the greater will be the hardness of the steel, and the stresses resulting from unequal cooling of sections of unequal size. Rapid coolings always, and accelerated coolings sometimes, must be followed by a second heating to a lower temperature to reduce hardness and relieve stresses. Accelerated coolings should be followed at least by a period of slow cooling, as, for instance, by closing the furnace again after the castings have cooled to black heat.

The temperature used for reheating after rapid cooling should not exceed 680°, if the castings have been quenched in oil or water, and should not exceed 720°, if the castings have been cooled in air or air blast. The castings should be held at these temperatures a sufficient length of time to produce the softening effects desired. Quenched castings, which may be reheated to from 640 to 680°, should be held at the reheating temperature from two to eight hours. Air-cooled castings, which may be reheated to from 660 to 720°, should be held at the reheating temperature from two to six hours. The lower the reheating temperature and the shorter the reheating time, the higher will be the strength and elastic limit of the steel, and the less the toughness, as measured by extension, contraction of area, bend and shock test. Reheating to temperatures that liberate coarse ferrite causes great loss of strength and toughness.

In general, the more rapid the cooling from the annealing temperature, if proper reheating temperature and time have been used, the greater will be both strength and toughness—these properties bearing a direct relation to microscopic fineness of structure. More especially, the shock toughness of soft and medium soft steel is greatly increased by rapid cooling and proper reheating.

The maximum softness, and the maximum magnetic permeability, however, are attained by very slow cooling from the annealing temperature, which results in the liberation of the maximum amount of free ferrite.

In selecting a method of heat treatment for a given casting, careful attention should be given to the size and intricacy of the piece, and especially to the possibility of cracking it if quenching is attempted. Frequently also, it will be impracticable to remove a casting from the furnace while hot, in order to quench it or cool it in the air, on account of the danger of bending it seriously. In such cases, accelerated cooling by opening all doors, etc., of furnaces, followed by proper reheating, will give good results.

In the majority of cases, accelerated or air cooling after reheating may be resorted to without setting up harmful stresses.

The maximum allowable reheating temperatures are those which effect the softening and relief of stresses in the least possible time, without resulting in the liberation of free ferrite in heavy masses. For the greatest toughness, the maximum time quoted must be used. That no harmful stresses are produced by air, or even water, cooling from the reheating temperature, has been proved by careful tests on stress test bars, and on full-sized castings of various shapes. That no hardening is thus produced has been carefully proved by experiment, and it is to be expected, since hardening results only on cooling steel after it has been heated above Ac1, and the reheating temperatures given do not exceed Ac1.

The author's experience of several years in the heat treatment of cast steel has shown conclusively the falsity of the widely held opinion that rapid cooling, and especially quenching, of steel castings, is almost sure to result in dangerous stresses and many cracked and broken pieces. Of course, very heavy sections, especially of hard steels, cannot be quenched without rupture. To quench successfully a solid spherical or cylindrical casting 8 or 10 in. in diameter, is well-nigh impossible. But if the steel is not too high in carbon, castings with quite widely varying sections, in all weights from a few pounds up to at least a ton, can be quenched in oil or even in cold water without the loss of a single piece, especially if they are not allowed to grow dead cold in the water. In the reheating, of course, the furnace men must take pains to heat these quenched castings up slowly until they reach a temperature of 300 or 400° C., but the work presents no difficulties not easily mastered by men familiar with the handling of high-grade steels. In a paper read before the American Foundrymen's Association, Mr. Stoughton[1] has called attention to the advantages of heat treatment of ordinary steel castings. In a recent article in the technical press,[2] the possibilities of these methods were disposed of in a few words. The writer of this article found that air cooling produced greater strength, etc., than slow cooling, but that to preheat the steel to a higher temperature, air cool it, reheat to the ordinary annealing temperature, and cool slowly, left the steel in the same condition as if it had been once annealed and slowly cooled. Very naturally, a slow cooling from the ordinary annealing temperature produced identical results in two castings, one of which was slowly cooled after one heating to this temperature, the other preheated, air cooled, then re-

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[1] Proceedings American Foundrymen's Association, Vol. XX, p. 451.

[2] Edwin F. Cone, *The Iron Age*, May 1, 1913, p. 1049.

heated to the ordinary annealing temperature, and slowly cooled. How the double heating, so carried out, could be expected to give superior strength to the steel, is hard to understand. It is as though a blacksmith should say that it is useless to harden a chisel, because a second heating to the hardening heat, followed by slow cooling, leaves the steel dead soft. Just as the "tempering" of a hardened chisel has to be carefully controlled, in order to "draw the hardness" to just the right degree, so air-cooled or quenched cast steel must be carefully reheated to just the right temperature, to relieve the cooling stresses and draw to the required extent the hardness due to rapid cooling.

The Value of Heat Treatment of Hypo-eutectoid Cast Steel.—A test of some kind to reveal brittleness under shock is of great value in judging the effect of heat treatment. There are a number of impact testing machines now on the market, most of which use a notched test piece of small cross-section, which is broken by a heavy blow from a falling weight or pendulum provided with a knife edge to come in contact with the test piece. The force consumed in breaking the test piece is the measure of the brittleness of the steel, and the deflection of the test bar before rupture is a further indication of value. The force recorded is the sum of that necessary to effect the elastic deformation, and that necessary to effect the plastic deformation and rupture of the test piece. Because the plastic deformation of hard steels is slight (that is, they break without bending very far), while that of soft steels is very great, the total amount of force needed to break a soft steel and that required to break a hard steel in this test, are quite disproportionate. The test, therefore, should not be used to compare steels of varying carbon content. But to ascertain the toughness of a particular steel, as affected by heat treatment, it is of great value.

It has been suggested that by measuring the angle of bend in this test,[1] a basis may be found on which to subtract the work done in overcoming plastic deformation from that expended in overcoming elastic deformation and affecting rupture, and thus that a means may be found of using the test to compare different steels.

Fremont's machine tests a bar about $\frac{1}{4}$ in. by $\frac{3}{8}$ in. by 1 in., notched with a hack saw, and broken by the blow of a weight of 10 kgm. falling 4 meters. Charpy's testing machine is of the pendulum type. Several other designs are on the market.

In a paper[2] presented at the 1913 fall meeting of the American

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[1] Professor Henry M. Howe, Discussion of the author's paper, referred to below.

[2] Shock Tests of Cast Steels.

Institute of Mining Engineers, the author has pointed out what, at least in his opinion, is the weak point of this method of testing as applied to steel castings; that is, the wide variation in the value of the impact test from different parts of the same coupon of heat-treated cast steel. Two conclusions can be drawn from these variations: first, that the test is not reliable as an indication of the average toughness of heat-treated cast steel in any but very light sections; second, that the extreme toughness obtainable by quenching and reheating mild cast steel is confined to the outside half inch or so of thicker sections.

Experiments carried on for a period of years have shown conclusively that the presence of coarse ferrite, especially if it exists in a net-work structure, or in a partially developed net-work structure, whether formed on slow cooling from the annealing temperature, or on reheating after rapid cooling, to temperatures that allow the liberation of such ferrite, is always accompanied by more or less brittleness of the steel; and this brittleness is particularly marked when the steel is tested under sudden shock. This statement applies to all *coarse* ferrite microstructures, even if the structure is uniform.

This conclusion is in agreement with Mr. A. Le Chatelier's results on brittleness of steel.[1] That eminent authority has shown that in any hypo-eutectoid steel which has been cooled slowly after being heated above $Ac3$, though under slow tensile testing very considerable toughness is exhibited, yet as the speed of testing is increased, the toughness decreases, and when the speed of testing is so great that the ultimate strength of the steel is reached almost instantaneously (shock test), the test bar breaks practically without elongation or contraction of area. On the other hand, quenched and reheated steels, provided the reheating temperature does not exceed 700° C., exhibit as great toughness when tested by shock tensile test as when tested by the usual slow tensile test.

In the table below are given the physical properties and heat treatments of test bars cut from a single casting of steel containing .10 per cent. carbon, .19 per cent. silicon, and .23 per cent. manganese.

Blow holes made it impossible to secure tensile tests on two of the bars, and one bending bar that undoubtedly should have bent 180 degrees was spoiled by a blow hole. It is particularly to be noted in these tests that the superiority of the heat-treated over the raw steel,

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[1] Congrès International des Méthodes d'Essai des Materiaux de Construction, Paris, 1900, Vol. II., part I, pp. 13–25—see especially p. 16, paragraph 4.

as judged by the tensile test alone, is not very great; as judged by the bend, is considerable, without revealing any variation in the toughness of the bars heat treated by the several methods; but as judged by the shock test, the toughness is improved some four-fold in the annealed and slowly cooled bar, seven-fold in the air-cooled and reheated bar, eight-fold in the bar cooled at an accelerated rate, and ten- to eleven-fold in the quenched bars, whether reheated or not. The shock test of 2.5 kgm., given by the raw steel, is extremely low; and the breaking of this specimen without measurable deflection, with a coarse crystalline fracture, confirmed the reading of the machine. The two tests that gave 25 and 27.5 kgm. did not break. It would be difficult to find a more striking example than this of the inadequacy of slow tensile testing alone, or even in combination with a bend test, to reveal even very considerable brittleness. That cast steel of .10 per cent. carbon requires annealing at all, is not admitted by many foundrymen. Yet, as the tests show, not only does it require annealing, if used for any purpose demanding toughness, but if the maximum resistance to suddenly applied stresses is to be secured, castings of even this very soft steel should be quenched, and of course, reheated to relieve stresses (the actual hardening of such a steel by quenching is too slight to affect the usefulness of the castings).

No.	Treatment Temperature and time	Tensile strength	Elastic limit	Ext. % in 2 in.	Cont, %	Fracture	Bend ½ in. × 1 in., on 1-in. mandrel	Fremont, kgm.
A	none	50,020	23,930	35.2	47.85	Coarse cryst.	50	2.5
B	900–3 cool in 40 minutes	55,390	28,750	38.5	67.0	Silky cup	180	20.0
C	900–3 cool slowly	....	....	......	......	....	45 (blow hole)	10.5
D	900–3 quench	....	....	......	......	....	180	27.5
E	900–3 air cool 710–6 air cool	56,450	32,950	39.25	65.2	Silky cup	180	17.5
F	900–3 quench 680–8 air cool	53,200	27,100	34.95	60.4	Silky cup	180	25.0

Medium carbon steels, especially those containing a large proportion of manganese, are made tremendously strong, and at the same time very highly resistant to shock, by rapid cooling and reheating. Examples could be given of the results of several years' experience with such steels, but only a few will be quoted. They are, however, typical.

Fig. 32 shows the microstructure of a steel containing .21 per cent. carbon and 1.17 per cent. manganese, heated to 900° for five hours and quenched in water, then reheated to 650 to 680° for six and one-half hours and cooled in air. This microphotograph was taken from a test coupon attached to a large casting; the physical properties of the bars cut from this coupon were:

TS	EL	Ext. % in 2 in.	Cont., %	Fracture	Bend	Fremont, kgm.
91,900	71,650	20.37	50.25	Silky	180	21.0

The very high shock test and bend, coupled with great strength, is particularly noticeable.

Figs. 33 and 34 show the microstructures of two small castings. They were too small to cut tensile or bending tests from them, but a bend of a projecting lug of one casting was made, the lug being bent flat on itself without fracture. The analyses and Fremont tests of these castings were:

Fig.	C	Si	Mn	S	P	Fremont, kgm.
33	.18	.41	.93	.065	.052	5.0
34	.20	.45	1.02	.057	.049	7.0

The very low shock test value, despite good slow bending toughness, is especially to be noted. The shock tests broke with almost no deflection, and showed a rather coarse crystalline fracture, practically identical in both. This coarse fracture of the shock tests of such steels is typical. The annealing of these castings had been by heating and slow cooling, and was very insufficient in No. 34, as the microstructure shows. Yet, the Fremont tests were about alike, even slightly better for No. 34 than for No. 33.

Casting No. 34 was sawed into two approximately equal parts, and one-half heat treated as follows: Heated to 900° for four hours and quenched in water, reheated to 680° for eight hours and cooled in air. The two halves, one in the annealed, the other in the heat-treated condition, were then subjected to the blows of a drop of about 500 lb. falling weight, with the result that the annealed half broke in three pieces at the first blow of the drop from a height of 4 ft. showing a coarse crystalline fracture; while the heat-treated half endured without fracture one blow from 4 ft., one blow from 5 ft., one blow from 6 ft., one blow from 7 ft. and two blows from 8 ft.; six blows in all. The two halves of the casting, after test, are shown in Fig. 35, annealed half (three pieces) to the left, heat-treated half (one piece) to the right. In Fig. 36 a back view of the heat-treated half, after test, is shown.

This drop test confirms the result of the Fremont test, which showed that the castings as annealed were brittle under suddenly applied heavy load, though they gave a good bending test. No section of these castings was over 1 in. thick, and the average thickness was about ½ in. The impact test is excellent for revealing brittleness in thin castings of this sort.

A rough test used by the author to demonstrate the toughness of heat-treated cast steel in heavier sections consisted in striking a 2½-in. square bar of the steel, resting on supports 24 in. apart, with a drop of about 500 lb. weight, falling some 10 or 12 ft. A 2-in. round bar was set in the middle of the test bar to localize the shock, and the test bar reversed after each blow. The result was a sort of accelerated endurance test under shock, the bars being deflected about ½ in. at each alternate blow, and straightened by each alternate blow. Of course, the greater toughness of the outside fibers, which are subjected to the maximum stress, increases the resistance of the bars to fracture in this test. Quenched and annealed bars of steel of about .25 per cent. carbon and 1.20 per cent. manganese, tested in this manner, have endured from 28 to 57 blows before rupture. What was particularly noteworthy in the performance of these bars was that frequently they exhibited cracks completely across each face, and extending some ¼ in. into the bar, three or four blows before final rupture took place, indicating very considerable toughness and resistance to the spreading of the cracks in the interior portions of the test bars.

Another rough test, used to exhibit the toughness of castings treated by quenching and reheating, was adopted for castings having an eye some 6 in. in internal diameter and 2 ft. long, with walls about 2½ in. thick, used to fasten these castings by means of a heavy pin, to another part of the machine. A hard steel wedge of suitable taper was seated in this eye, and then driven down by the blows of a heavy drop, weighing about 1500 lb. and falling about 12 ft. Quenched and annealed steel castings (.25 per cent. carbon, 1.20 per cent. manganese, of about 85,000 lb. tensile strength), so tested, endured from eight to fourteen blows before rupture; and in some cases the wedge could be driven no further with the drop employed. The rupture of the walls of the eye almost invariably followed an irregular line, the steel tearing slowly apart. No comparison with steel of the same carbon, annealed by heating and slow cooling, was made, but compared with higher carbon castings of approximately equal strength, the results of the tests were most illuminating, the harder steels never enduring over two blows. The second blow on the harder steel castings sent the fragments, or sometimes the whole eye, hurtling across the shop.

That these castings possessed great strength and toughness is demonstrated by the fact that in service they wore down on one side of this eye, which endured very heavy stresses applied somewhat suddenly, from the original thickness of some 2½ in. to a thickness of ¼ in., without rupture of the eyes.

The following figures are given to show the physical properties of a number of test bars, selected at random, cut from these castings. Each group represents a lot of tests made on the same day, though not in every case from the same annealing furnace.

Tensile strength	Elastic limit	Ext. per cent. in 2 in.	Cont., per cent.	Fracture	Fremont, kgm.	Bend ½ in. by 1 in., on 1-in. mandrel
88,850	63,500	26.60	52.9	Silky cup	19.0	180
88,300	61,240	28.11	54.75	Silky cup	14.0	180
89,600	60,400	26.19	47.3	Silky cup	15.0	180
85,950	60,400	28.36	59.05	Silky cup	22.0	180
89,200	61,020	26.19	51.0	Silky cup	11.0	180
100,000	70,820	23.8	49.65	Silky cup	23.5	180
92,850	62,300	24.66	55.6	Silky cup	15.0	180
90,100	60,200	26.95	58.75	Silky cup	13.0	180
98,800	66,680	22.80	48.75	Silky cup	24.0	145
88,550	60,600	26.60	54.4	Silky cup	11.0	180
96,150	65,070	25.57	57.15	Silky cup	15.0	180
90,000	55,100	31.05	56.3	Silky cup	15.0	180
85,100	55,970	29.14	58.8	Silky cup	30.0	180
80,800	51,510	29.14	62.5	Silky cup	28.5	180
90,700	62,780	27.2	56.6	Silky cup	25.5	180
85,950	51,040	25.26	58.6	Silky cup	30.0	180
83,450	51,700	29.69	60.45	Silky cup	27.5	180

Endurance Test.—Under ordinary conditions of service, of course, a casting will never be strained beyond the elastic limit, and therefore a casting of soft steel heat treated to give great shock toughness, will not be called upon to exhibit the plastic deformation which it is capable of enduring. A casting used, for instance, for the front axle of an automobile, will have a very long life under ordinary conditions of service, if it is capable of enduring a great number of stresses repeated constantly, none of which exceeds the elastic limit. We know that the higher the elastic limit of a steel, the higher in general will be its resistance to repeated stresses of a given intensity. As the elastic limit rises in proportion to increase in carbon content, it is in general better to use a medium high carbon steel for an axle than to use a soft steel, under ordinary conditions of service. Experience with locomotive axles has proved this to the satisfaction of engineers.

In certain classes of service, however, allowance must be made not only for ordinary, but for extraordinary, conditions. Thus, for instance, some manufacturers of taxicabs who use a cast steel front axle, make one portion of the casting sufficiently light to either bend or break, and thus save the rest of the car from injury, when it collides with some heavy object. In practice, they find that some of their axles have been so bent, straightened and returned to service, several times. Now, for such service as this, in which it is expected that the steel will occasionally be strained far beyond its elastic limit, a steel of great shock toughness and which will endure plastic deformation will be of value in two ways. First, in such an accident, it will be far less apt to break than a hard steel, and hence will in many cases prevent a serious smash-up. Second, such a steel can be bent and straightened more times than a more brittle steel, so that its use will result in a saving of money spent on replacement.

In order that such a steel should possess a good resistance to repeated stresses which do not exceed the elastic limit, it should be heat treated in such a way as to give it the maximum strength. It is true that, by so treating a hard steel, it will be given much greater resistance to repeated stresses than can be given to the soft steel. But the hard steel can never possess great shock toughness.

In the following tables, unfortunately based on but few examples, it is shown that a soft cast steel, quenched and annealed, will possess a tensile strength and elastic limit equal to those of a much harder steel annealed in the usual manner by heating and slow cooling, or heat treated by air cooling and reheating; and that the endurance of the soft steel so treated, to alternate stresses, at least of this type, is greater than that of the harder steel. Leaving out test *C*, five bars of the harder steel endured an average of 3,805,000 revolutions at a fiber stress of 28,270 lb. to the square inch; and five bars endured an average of 10,451,240 revolutions at 28,270 lb. to the square inch, and 590,560 revolutions additional at 38,870 lb. to the square inch. The four bars of the softer steel endured an average of 10,373,050 revolutions at 28,270 lb. to the square inch, and 823,950 revolutions additional at 38,870 lb. to the square inch. In every case but one, the soft steel gave a better test than the hard steel. These tests were made on the White-Souther endurance testing machine.

No.	Cut from	C	Si	Mn	S	P	Treatment		
							Heated to	For	Cooled
A	4 in. sq.	.42	.46	.73	....	....	900 degrees 700 degrees	5⅓ hours 5½ hours	air slowly
B	4 in. sq.	.44	.38	.59	....	....	900 degrees 690 degrees	5 hours 3 hours	air slowly
C	4 in. sq.	.48	.42	.71	....	....	960 degrees	? hours	slowly
D	4 in. sq.	.36	.54	.71	.049	.051	920 degrees 690 degrees	5 hours 3 hours	air slowly
E	4 in. sq.	.47	.56	.73	....	....	900 degrees 700 degrees	5½ hours 11 hours	air slowly
F	4 in. sq.	.43	.46	.65	....	....	900 degrees 700 degrees	4 hours 5 hours	air slowly
G	1¼×2½ in.	.23	.31	1.07	.037	.047	900 degrees 680 degrees	6 hours 8 hours	water air
H	4 in. sq.	.27	.46	.71	....	....	900 degrees 680 degrees	5 hours 8¾ hours	water air

No.	T S	E L	Ext. in 2 in., per cent.	Cont., per cent.	Fremont
A	82,100	45,990	8.41	9.79	7.5
B	76,170	42,990	14.64	15.11	5.0
C	76,730	42,750	12.05	15.81	5.0
D	73,200	40,630	14.08	19.79	10.0
E	79,590	44,020	10.94	11.49	8.5
F	73,200	40,200	12.5	16.4	7.5
G	67,200	44,400	14.19	31.3	32.0
H	78,710	46,400	22.8	24.21	17.0

ENDURANCE TEST

No.	Fiber stress	Deflection	Revolutions No. 1 end	Revolutions No. 2 end
A	28,270	.06	10,709,600	10,709,600
B	28,270	.06	4,685,000 (B)	6,708,000 (B)
C	28,270	.06	2,796,800 (B)	10,000,000+[1]
D	28,270	.06	3,474,300 (B)	2,368,700 (B)
E	28,270	.06	10,158,400	1,789,400 (B)
F	28,270	.06	10,339,300	10,339,300
G	28,270	.06	10,475,100	10,475,100
H	28,270	.06	10,271,000	10,271,000

No.	Fiber stress	Revolutions No. 1 end	Revolutions No. 2 end
A	38,870	280,800 (B)	302,000 (B)
B	...	...	...
C	38,870	...	288,700 (B)
D	...	...	...
E	38,870	1,828,600 (B)	...
F	38,870	366,000 (B)	175,400 (B)
G	38,870	393,900 (B)	845,500 (B)
H	38,870	834,100 (B)	1,222,300 (B)

B signifies bar broke.

[1] Exact number uncertain.

As already stated, it would no doubt have been possible by quenching and annealing the hard steel, to make it superior to the soft steel in this test, but the heat treatment would not have given the hard steel a much greater resistance in the impact test. Hence, although an automobile axle made of the hard steel quenched and reheated, would probably give longer life under ordinary conditions of service than the soft steel similarly heat treated; yet in case of a smash-up, there is little doubt that the hard steel would be broken short off by a blow which the softer steel would endure without rupture. In order, therefore, to have in our machinery parts a steel which will resist both repeated light stresses and occasional heavy stresses, we should use a comparatively soft steel which has been quenched and annealed. The automobile front axle is of course a very special case, and is seldom made of cast steel. It is referred to here, however, as a striking example of a type of service for which many machinery castings are made.

Experience with marine engine shafting and steam hammer piston rods has shown in many cases that a heat treatment which gives the steel great shock toughness will increase the life of the forging even as much as five- or six-fold.[1] What is true of forgings will be equally true of castings, except that because a casting almost inevitably contains small blow holes or flaws, it can never be made as reliable as a forging, so that the lengths of life of a number of similar castings will not be so nearly equal as would be true of forgings. But to maintain, as some quite competent engineers do, that because a casting is a casting, and almost sure to contain flaws or blow holes, it is not worth while to heat treat cast steel to give great toughness, is most illogical. It is certainly poor reasoning to say that because a casting is almost sure to contain a starting place for a crack, it is not worth while to treat the steel to make it as resistant as possible to the starting and spreading of that crack.

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[1] Professor Henry M. Howe, discussion of the author's paper "Shock Tests of Cast Steels" referred to above.

High Carbon and Alloy Cast Steels.—Hyper-eutectoid cast steels, that is steels containing over .89 per cent. of carbon, and therefore consisting of pearlite and free cementite, are very little used. Their heat treatment has, therefore, not been worked out with the same thoroughness as that of mild steels. It follows from a consideration of the carbon-iron diagram that the heat treatment of these steels must be similar to that of hypo-eutectoid steels. Annealing must be at a temperature above the line *SE* in order to dissolve the cementite in the austenite, and the effect of varying the rate of cooling should be quite similar. The researches of Boynton[1] on hyper-eutectoid rolled steels have shown that by hastening the cooling from above the line *SE*, the separation of cementite can be largely suppressed. The temperatures for reheating should be the same as for hypo-eutectoid cast steels.

Chrome and nickel cast steels, containing about 1 per cent. of chrome, or $2\frac{1}{2}$ to $3\frac{1}{2}$ per cent. of nickel, and of carbon below the eutectoid ratio, which, like carbon steel, contain in the normal condition free ferrite, exhibit somewhat marked differences in the effect of annealing, from the behavior of the carbon steels. This is particularly noticeable in the case of slow cooling after heating above $Ac3$. In these steels, though on slow cooling free ferrite appears, yet the distribution of this ferrite in heavy masses is much less marked than in carbon steels. Annealing and slow cooling of these steels, therefore, produces a much more uniform microstructure. The same rules as to increase of toughness and strength by special heat treatment methods, however, apply with almost equal force to these alloy steels.

The addition of nickel to steel lowers the critical points to a degree proportional to the amount of nickel added. The annealing and reheating temperatures, therefore, can be lowered to a corresponding degree, though it is by no means essential to do so. But as the sluggishness of the molecular changes in steel increases as temperature falls, the time of exposure to these temperatures should be increased in proportion as the temperatures themselves are lowered.

Manganese steel, containing, as usually made, from 10 to 15 per cent. of manganese, and from .80 to 1.5 per cent. of carbon, is heat treated by methods quite different from those followed for ordinary cast steel. By the combined effects of carbon, manganese and rapid

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[1] *Iron and Steel Magazine, May,* 1904.

cooling, manganese steel is rendered entirely austenitic and very tough, because the transformations are nearly or quite suppressed. In the cast condition, or when heated and slowly cooled, this steel is very brittle, owing to partial transformation of the austenite, and to the liberation of free carbide of iron and manganese (manganiferous cementite?), between the austenite grains.

As the steel is quenched from a high temperature, generally over 1000° C., the castings, if of unequal section, are left after treatment in a state of heavy stress. Relief of these quenching stresses is, moreover, extremely difficult, as to reheat the steel to a temperature high enough to relieve them, results in great brittleness of the steel.

The brittleness of the steel when cast; its high shrinkage, which results in heavy stresses in cooling in the mould and in treatment; and its low thermal conductivity; these properties make the design and heat treatment of manganese steel castings of complicated shape a difficult and fascinating task.

Annealing Furnaces.—Annealing furnaces are built in a great variety of designs, and almost any fuel may be burned in them. Coal, fuel oil, natural gas, or even occasionally producer gas, may be used, depending upon the price of the fuel. Producer gas, however, which requires regeneration for its combustion, is not commonly a good fuel for this purpose, since annealing furnaces generally have to be cooled off very considerably between heats, and often lie idle for many hours. Such conditions interfere seriously with the operation of a furnace that is at its best only when run continuously, and prevent the attainment of the economy that regenerative furnaces will give under suitable conditions.

In general, annealing furnaces should not be built large enough to take the entire day's output of a foundry at one charge, particularly if the size of the castings varies considerably. The practice of charging large and small castings in the same furnace is a very poor one, since if time enough is given the large castings to heat through properly, the small ones suffer from oxidation and consequent scaling; and a real loss is experienced in that the small castings are heated much longer than necessary, at a considerable expense in fuel.

Very large annealing furnaces, heated by one or more fire boxes so small that the temperature in the furnace will vary considerably from point to point, are most inefficient for two reasons, if not more. First, the castings at the "cold" points are seldom properly annealed; second, those at the "hot" points are annealed longer than need be, in an effort to bring the "cold" castings up to a proper heat.

Considered from this standpoint, the large "catch all" annealing furnace is most uneconomical, and it is extremely doubtful if the saving in labor attained by its use is sufficient to offset its great wastefulness in fuel and the poor quality of its work. One man can fire three small furnaces nearly as easily as one large one—quite as easily if oil or gas fuel is used—and if the three or more furnaces are designed with a view to making them suitable to the size of castings that are to be annealed in them, an economy of fuel will result from their use.

The deep furnace with a lift-off top gives great economy in charging labor, and when used for castings that are to be annealed by slow cooling, or accelerated cooling, does fairly good work. If heat treatment, properly so-called, is to be used, so that the castings have to be taken from the furnace for quenching or air cooling, it will frequently be necessary in such a furnace to set them on a heavy steel plate that can be lifted out. To remove castings one at a time from an open-topped furnace will not be very easy; and if they must not be allowed to cool before quenching, it will be hard to get them all out in time. Though the castings are generally piled in these furnaces more or less haphazard, it will in most cases be best to set them up more carefully so that they can be heated evenly and will not suffer from warpage.

The side-drawing furnace with a movable bottom is in most cases the best type to install, when heat treatment is to be used. They are more costly to build than open-top furnaces, but can be charged quite as cheaply, and make it easy to withdraw the castings one at a time for quenching, without cooling off the rest of the charge; or to take out a number of comparatively small castings set on plates and quench them in batches. A side-drawn furnace with fixed bottom can of course be used for the same work, by charging and drawing with piels, but the labor expense in such work is very great.

Continuous furnaces may be used for the heat treatment of very light work, if there is a great deal of it to be done. Such furnaces are often used to anneal small forged parts, and can of course be utilized to equal advantage for small castings.

Pyrometers.—Temperature control in steel casting annealing, has long been one of the weakest points in the practice of the shops, and lack of proper precautions to ensure correct annealing temperature has been almost universal. So common has been the practice of annealing steel castings without control of temperature, that in the majority of shops heat treatment has had no chance of success.

The great majority of castings require only annealing by heating and slow cooling; or at most, by accelerated cooling, followed by slow cooling to relieve strains. For such work, it may sometimes be possible to estimate the temperature closely enough by the eye, but when the eye is relied upon it will be found that no two heats will be annealed quite alike, because the man is not yet born who can recognize small temperature intervals by color. For the heat treatment of ordinary steel, the heating of alloy steels, and all work where the temperature must be closely controlled, pyrometers are absolutely indispensable; and their general use is advisable.

In practice, however, the use of pyrometers is not an absolute guide to the temperature of the castings, since it is neither economical nor sensible to install enough thermocouples in each furnace to give its temperature throughout. The eye must always be relied upon to a great extent to make sure that the steel throughout the furnace has reached the correct temperature. With one or two thermocouples in the furnace, the fireman can heat his steel quite uniformly to a prescribed temperature, because he can *match* colors very well indeed, and can bring all the castings to the color of the spots where the couples are. In this way he can do far more accurate work than is possible even by the use of a painted color scale; such a scale is not as useful as might appear, because the color sensation produced on the eye by a hot object is not capable of being matched closely against that produced by a painted board.

The men, however, should not be allowed to fall into the habit of simply heating up the furnace until the pyrometer indicates the correct temperature, holding the pyrometer at that temperature the proper length of time, and then cooling off the furnace or drawing the castings, as the case may be. Once taught to rely entirely upon the pyrometer, they consider that the burden of responsibility for the proper annealing of the steel has been shifted from their shoulders to those of the man who standardizes the pyrometers, and they no longer take pains that the steel shall all be at the temperature desired. Perhaps the best way to secure their attention to their work is by the use of test bars attached to various castings, or charged with the steel at several points in the furnace. A few test bars in every heat have a wonderful effect in making the men "sit up and take notice," and even if they are never tested at all (so long as the men do not find it out), are extremely useful. Used for tests, recorded in such a way as to be readily consulted and compared, they are invaluable.

At least one recording galvanometer should be installed, in addition to the direct-reading instruments, arranged so that it can be switched on to any furnace, or any two, three or more furnaces at once. Needless to say, the connections to this instrument should be entirely beyond the control of the men, and they should never know on what furnace the recording instrument is reading. Under these circumstances, especially when the pyrometer man comes around several times a day and makes sure that the instruments are all reading correctly, the men hesitate to try to cover up errors in the temperature of the furnace, lest the recording instrument "show them up." It is an excellent scheme to require the firemen on the furnaces to keep a record of their pyrometer readings at suitable intervals, on blanks provided for the purpose, because if they must read the instruments and record the readings, subject to check by the automatic galvanometer, they will be pretty sure to keep their furnaces at the right temperature.

No pyrometer system yet invented is "fool proof," nor a substitute for care and conscientious work on the part of the fireman, nor an absolute guide to correct annealing and heat treatment, but properly handled, such an installation is so useful and removes so much uncertainty that after a few months' use it appears well-nigh indispensable.