DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 192

TESTS OF CENTRIFUGALLY CAST STEEL

BY

GEORGE K. BURGESS, Physicist

Bureau of Standards

JUNE 7, 1921

PRICE, 10 CENTS

Sold only by the Superintendent of Documents, Government Printing Office
Washington, D. C.

WASHINGTON
GOVERNMENT PRINTING OFFICE

1921

TESTS OF CENTRIFUGALLY CAST STEEL

By George K. Burgess

ABSTRACT

Six castings manufactured by the Millspaugh centrifugal process were examined as to their physical and chemical properties, including hardness, tensile strength, impact resistance, density, internal stress, segregation, soundness, and microstructure, both in the condition as cast and after various heat treatments. This investigation shows the possibilities of substituting heat treatment for forging in this type of casting.

CONTENTS

	Page
I. Introduction.....	3
II. Dimensions of castings and of test samples.....	4
III. Tests of castings.....	4
1. Hardness and chemical surveys.....	4
2. Density determination.....	7
3. Investigation of stresses across section of rings.....	8
4. Heat treatment and mechanical properties.....	9
5. Macrostructure and microstructure.....	11
IV. Summary.....	15

I. INTRODUCTION

In 1918 the Bureau of Standards had occasion to examine several hollow steel cylinders made under the direction of W. H. Millspaugh by his centrifugal casting process. The manufacture of these centrifugal castings was carried out under somewhat adverse conditions in two steel foundries which, of course, due to the limited experimental nature of the trials, could not have developed the refined technique that practice would give, nor were efforts made to produce high-grade steel for these tests.

The cylinders were cast in a machine revolving about its horizontal axis. The outer surface of the castings, of walls from $3\frac{1}{2}$ inches to $\frac{1}{2}$ inch thick, were thus against the mold and turning faster than the free inner, cylindrical surface, which was last to reeze. The outer surfaces were fairly smooth, but the interior surfaces were rough.

The results, comparing the several grades of steel in the condition as cast and after heat treatment, are of considerable interest as indicating what may be expected from this method in the

production, for certain shapes, of sound steel, that is, free from physical defects and chemical segregation, and thus with practically no waste material to discard. As will be shown, it is also a field particularly adapted to the elimination of forging and boring operations and the substitution for the former of heat treatment to produce the desired characteristics in the resulting product.

II. DIMENSIONS OF CASTINGS AND OF TEST SAMPLES

In all, six castings were examined, samples from which were subjected to the usual mechanical tests, both transverse and longitudinal, in the condition as cast and after various heat treatments. The characteristics of the metal with respect to internal stress, density, soundness, segregation, and microstructure were also studied.

In Figs. 1 and 2 are shown the dimensions of the castings and location of samples for test, except for No. 7, a cylindrical ring 12 inches in diameter and having a wall thickness of $\frac{1}{2}$ inch, from which longitudinal flat tensile bars 12 inches long by 1 inch by $\frac{9}{32}$ inch were taken. The tensile bars from all other castings were standard 2-inch round bars. Samples for chemical analysis were taken in ring turnings for Nos. 4, 5, and 7, and for Nos. 1, 3, and 6 from longitudinal borings in zones numbered 1 to 5 from outside to inside of the casting (Figs. 1 and 2).

III. TESTS OF CASTINGS

1. HARDNESS AND CHEMICAL SURVEYS

In Table 1 are given the results of the radial surveys for hardness and chemical analysis. It will be noted there is a gradual increase in carbon from the outside to the inside surface for all castings, this increase ranging from 0.02 per cent for No. 3A to 0.09 per cent for No. 5; it appears to be roughly proportional to the carbon content, or the percentage variation in carbon remains practically constant. The nickel and phosphorus appear to follow the carbon very closely in their behavior as to segregation; manganese and silicon, on the other hand, are nearly constant across the radial section; while sulphur, although somewhat erratic, in general is distributed similarly to carbon, as is also copper, although present in quantities less than 0.1 per cent. The hardness surveys, Brinell and scleroscope, follow closely the chemical segregation, the higher numbers occurring on the inside layers. A hardness survey with the scleroscope made midway along a longitudinal section the length (72 inches) of casting No. 1 at 3-inch intervals

shows a gradual increase in hardness from end *B* to the middle, 24.2 to 25.3, and then nearly uniform hardness for the second half, or from center to end *A*. (See Fig. 1.) The chemical analysis of

FIG. 1.—Castings 1 and 3, illustrating method of taking test samples

the *A* and *I* sections, separated by 60 inches in casting No. 3, apparently shows evidence of longitudinal segregation, but this is so very slight as to be uncertain.

FIG. 2.—Castings 4, 5, and 6, illustrating method of taking test samples

TABLE 1.—Results of Hardness and Chemical Surveys

Number	Wall thick- ness	Zone	Hardness		C	Mn	Si	S	P	Ni	Cu	Cr	
			Brinell	Sclero- scope									
Inches													
1.....	3½	{	1	186	25.8	0.44	0.44	0.47	0.024	0.011	2.33	0.084	0.04
			2	186	24.9	.48	.44	.47	.030	.013	2.35	.089	
			3	187	25.0	.46	.44	.47	.032	.013	2.32	.085	
			4	187	25.2	.46	.44	.48	.032	.014	2.36	.094	
			5	196	25.7	.50	.44	.47	.034	.015	2.39	.089	
3A....	3	{	1	160	22.3	.33	.54	.19	.022	.015	2.66	.051	.04
			2	164	22.2	.32	.55	.19	.030	.014	2.67	.053	
			3	167	22.4	.32	.55	.19	.032	.015	2.70	.051	
			4	167	22.6	.34	.57	.19	.034	.016	2.75	.055	
			5	160	22.3	.34	.57	.20	.030	.017	2.70	.054	
3I....	3	{	1	158	21.9	.30	.55	.20	.031	.012	2.66	.062	.04
			2	159	22.0	.30	.55	.19	.030	.013	2.67	.062	
			3	158	22.0	.30	.55	.20	.030	.015	2.68	.067	
			4	156	22.5	.34	.57	.20	.030	.017	2.76	.068	
			5	184	23.9	.35	.57	.21	.030	.018	2.60	.065	
4.....	2½	{	0			.16	.47	.27	.054	.045			
			1	125	19.7	.16	.50	.29	.045	.033	.....	.....	
			2	.....	20.4	.16	.51	.28	.045	.033	.....	.....	
			3	128	20.6	.17	.50	.28	.049	.037	.....	.....	
			4	.....	20.0	.18	.50	.29	.053	.038	.....	.....	
			5	121	19.2	.21	.52	.29	.060	.043	.....	.....	
5.....	3¼	{	0			.18	.40	.22	.066	.059			Tr
			1	249	63.5	.64	.56	.65	.033	.014	2.94	.....	
			2	.....	60.6	.65	.56	.65	.032	.015	2.92	.....	
			3	248	58.0	.63	.55	.64	.029	.015	2.93	.....	
			4	.....	55.5	.63	.55	.64	.031	.017	2.93	.....	
6.....	3½	{	5	245	57.0	.72	.60	.68	.033	.017	2.90		.04
			1	164	23.4	.32	.56	.19	.034	.015	2.69	.059	
			2	166	23.4	.33	.56	.19	.035	.015	2.75	.058	
			3	161	23.4	.31	.56	.19	.039	.015	2.72	.059	
			4	167	23.8	.33	.57	.19	.032	.015	2.76	.064	
7.....	½	{	5	191	25.2	.35	.57	.19	.033	.016	2.81	.064	
			1	.....	.....	.22	.54	.26	.026	.013	.....	.....	
			2	123	.....	.21	.53	.25	.026	.014	.....	.....	
		{	3			.25	.55	.25	.026	.016			

2. DENSITY DETERMINATION

A narrow circumferential strip 2 inches long, 1 inch broad, and ¼ inch thick was cut from the outside and from the inside of a transverse ring from the nickel-steel casting No. 3I and from the low carbon casting No. 4 and used for determination of density. The results are as follows:

Casting No.	Density g/cm ³ at 23°C	Difference
3I (outside).....	7.838	
3I (inside).....	7.834	+0.004
4 (outside).....	7.834	
4 (inside) ^a	7.726	+0.108

^a The low density of sample No. 4 (inside) is probably due to the presence of a series of very fine pits or blowholes in this sample. These holes occur about one-sixteenth inch from the inner surface of the casting, where their presence was actually observed.

3. INVESTIGATION OF STRESSES ACROSS SECTION OF RINGS

Three concentric rings, three-eighths inch wide (radially) and one-half inch thick (longitudinally), were cut from the No. 4 casting (low-carbon electric-furnace steel, annealed), one ring from the outside, one midway, and one from the inside of the cylinder. Accurate measurements were made of the outside and inside diameters of each ring, the distance between diametrically opposite punch marks, and the distance between three sets of punch marks 2 inches apart, tangentially. A cut was then made (by a hand hack saw) midway between the 2-inch tangential marks and at an angle of 90° to the diameter measured. When split thus the outer ring contracted visibly, but the middle and inner rings appeared to undergo no change. Similar rings were cut from casting No. 5 (high-carbon nickel steel, not annealed), measured and cut in the same manner as those from casting No. 4.

TABLE 2.—Survey of Stresses in Concentric Rings from Castings

Part	Casting No. 4			Casting No. 5		
	Before splitting	After splitting	Difference	Before splitting	After splitting	Difference
Outside ring:	Inches	Inches	Inch	Inches	Inches	Inch
Outside diameter.....	8.080	8.060	0.020 contraction...	10.765	10.750	0.015 contraction
Inside diameter.....	7.280	7.265	.015 contraction...	10.205	10.185	.020 contraction
Between punch marks (diameter)	7.650	7.625	.025 contraction...	10.515	10.505	.010 contraction
Between tangential punch marks.....	2.030	1.990	.040 contraction...	2.015	1.985	.030 contraction
middle....	2.000	1.960	.040 contraction...	1.985	1.950	.030 contraction
inner....	1.920	1.890	.030 contraction...	1.990	1.950	.040 contraction
Middle ring:						
Outside diameter.....	6.840	6.830	.010 contraction...	9.530	9.565	.035 expansion
Inside diameter.....	6.560	6.550	.000	9.080	9.095	.015 expansion
Between punch marks (diameter)	6.920	6.920	.000	9.345	9.355	.010 expansion
Between tangential punch marks.....	1.985	1.985	.000	2.000	2.015	.015 expansion
middle....	1.955	1.960	.005 expansion....	2.005	2.020	.015 expansion
inner....	1.900	1.900	.000	2.000	2.015	.015 expansion
Inside ring:						
Outside diameter.....	6.790	6.780	.010 contraction...	8.515	8.560	.045 expansion
Inside diameter.....	5.980	5.975	.005 contraction...	8.360	8.405	.045 expansion
Between punch marks (diameter)	6.425	6.445	.020 expansion....	8.160	8.175	.015 expansion
Between tangential punch marks.....	1.970	1.965	.005 contraction...	1.985	2.025	.040 expansion
middle....	1.955	1.950	.005 contraction...	1.975	2.005	.040 expansion
inner....	1.945	1.945	.000	1.975	2.005	.040 expansion

The measurements taken before and after cutting these concentric rings and the amount of expansion or contraction in each case are given in Table 2, and indicate the nature of the stresses in the outer, middle, and inner zones. A rough computation gives the compression at the outside ring of casting No. 4 as 48 000 pound per square inch, and for No. 5 the compression at the outside ring is 31 000 pounds per square inch, and the tension at the inside ring is 47 000 pounds per square inch. These internal stresses are of the order of the elastic limits of the material, and, as would be expected, the outer zone of the casting is in compression.

4. HEAT TREATMENT AND MECHANICAL PROPERTIES

Turning now to the question of the improvement of these castings by heat treatment, in Table 3 are given the details of the treatments to which material from the castings was submitted, and in Table 4 are grouped the mechanical properties associated with the respective treatments. The location of specimens is shown in Figs. 1 and 2. It should be recalled that castings Nos. 1, 3, 4, and 7 were annealed as a whole before any tests were made on them, while castings Nos. 5 and 6 were examined first in the condition as cast. The test pieces from 3A and 3I were from pieces of the same casting 60 inches apart. An examination of Table 4 shows that most samples show good tensile strength for their composition and treatment and also that there is no marked difference in values for longitudinal and transverse specimens. The values for the Izod shock test are somewhat erratic. The advantages of heat treatment, notably of the double quench and draw, in improving both the resistance to shock and especially the ductility as measured by reduction of area, are strikingly manifest. Certain of these treated steel castings would appear to compare very favorably in their properties with those of forged material of the same compositions. For example, the ordinance requirements for gun forgings are: Elastic limit, 65 000 pounds per square inch; tensile strength, 95 000 pounds per square inch; elongation, longitudinal 22 per cent, transverse 18 per cent; contraction of area, longitudinal 35 per cent, transverse 30 per cent. These are probably more than met by casting No. 6QQ ($C=0.33$, $Ni=2.75$ per cent) and almost met by others such as 3AQ and 3IQ ($C=0.32$, $Ni=2.70$ per cent). Again the properties of the casting

7 (C=0.23 per cent) are high for steel castings of that composition, and in the treated condition are superior to many of the results on hot-rolled 0.20 to 0.25 per cent carbon steels and indeed are comparable to those of cold-rolled steels of this grade.

TABLE 3.—Heat Treatment

Designation of sample	Condition received	Heat treatment given	Temperatures and time of heating						
			Heated slowly in air at the following temperatures	Then cooled. Held the following number of hours	Temperature when quenched		Quenching medium	Drawn 30 minutes at —	Cooled in
					First	Second			
1N...	Annealed	Normalized	800-805	2	°C	°C		°C	Air
1Q...	do.....	Quenched a n d drawn.	800-805	2	795-800		Water...	600	Do.
a3N...	do.....	Normalized	890-900	3					Do.
3Q...	do.....	Quenched a n d drawn.	890-910	3	845-850		Oil.....	640-650	Do.
4N...	do.....	Normalized	910-925	2					Do.
4Q...	do.....	Quenched a n d drawn.	910-925	2	915-925		Water...	450-460	Do.
4QQ...	do.....	Double quenched ..	910-925	2	915-925	885	do.....	440-450	Do.
5N...	As cast	Normalized	750-760	1½					Do.
5Q...	do.....	Quenched a n d drawn.	750-760	1½	760		Oil.....	700-705	Do.
6N...	do.....	Normalized.....	850-860	2					Do.
6Q...	do.....	Quenched a n d drawn.	850-860	2	825-830		Water...	675-680	Do.
6QQ...	do.....	Double quenched ..	850-860	2	825-830	790-795	do.....	680-690	Do.
7Q...	Annealed	Quenched and drawn.	875-880	1	875-880		do.....	510-515	Do.
7QQ...	do.....	do.....	880-885	1	880-885	845	do.....	435	Do.

^a Specimens from A and I sections of No. 3, same treatment.

TABLE 4.—Mechanical Properties

C and Ni	No.	Yield point (Divided by 1000)		Ultimate strength (Divided by 1000)		Elonga- tion in 2 in.		Reduction of area		Izod im- pact		Microstructure
		L	T	L	T	L	T	L	T	L	T	
		Lb in. ²	Lb in. ²	Lb. in. ²	Lb. in. ²					Ft. lb in. ²	Ft. lb. in. ²	
C, 0.44-0.50; Ni, 2.32-2.39.	IX	54.3	.....	91.2	.....	10.5	.....	12.1	.....	48.8	.....	Fairly fine with coarse ferrite boundaries, few slaggy areas. } Small blowholes
	IY	53.5	.....	50.5	.....	9.5	.....	8.9	.....	.....	.....	
	IT	.....	56.5	.....	89.5	.....	5.5	.....	7.5	.....	.....	
	IN	67.5	.....	93.0	.....	8.5	.....	12.5	.....	.....	.....	Fine uniform
	IQ	87.5	91.3	89.0	105.0	4.5	6.5	11.5	14.0	85.2	.....	Very fine uniform
C, 0.32-0.34; Ni, 2.66-2.75.	3AX	53.8	.....	89.8	.....	7.5	.....	12.1	.....	252.0	187.0	Fir-tree crystals and a few slaggy ferrite areas. } Ingotism
	3AY	48.5	.....	81.5	.....	16.5	.....	22.0	.....	.....	.....	
	3AT	.....	50.7	.....	78.2	.....	26.0	.....	42.5	.....	.....	
	3AN	59.8	.....	95.7	.....	16.0	.....	29.3	.....	.....	.....	Fine uniform.
	3AQ	67.5	70.2	98.0	90.3	21.5	20.5	47.4	42.0	309.0	704.0	Sorbitic, ferrite ghosts
C, 0.30-0.35; Ni, 2.66-2.76.	31X	52.5	.....	88.7	.....	14.8	.....	19.3	.....	.....	.....	Finer than 3A. } Very few slaggy areas
	31Y	48.4	.....	81.8	.....	27.0	.....	41.8	.....	.....	.....	
	31N	60.5	.....	89.1	.....	9.5	.....	18.5	.....	.....	.....	
	31Q	64.5	.....	95.5	.....	21.0	.....	29.9	.....	.....	.....	Do.
	4	40.0	.....	61.5	.....	16.5	.....	10.4	.....	34.5	48.4	Coarse with thick ferrite veins
C, 0.16-0.21....	4N	47.5	.....	65.0	.....	11.5	.....	18.9	.....	.....	.....	Fine, trace of veins
	4Q	60.0	.....	79.2	.....	13.0	.....	20.3	.....	247.0	304.0	Fine with streaks
	4QQ	55.0	.....	72.5	.....	12.5	.....	24.5	.....	.....	.....	
C, 0.63-0.72; Ni, 2.90-2.94.	5	48.0	65.7	85.0	84.7	2.5	1.0	1.2	1.0	16.3	16.1	Coarse pearlite
	5N	77.5	.....	129.0	.....	6.5	.....	5.4	.....	.....	.....	Fine slaggy pearlite areas
	5Q	96.4	92.3	115.0	113.3	16.5	7.5	21.7	10.5	142.0	183.0	
C, 0.31-0.35; Ni, 2.69-2.81.	6X	47.5	.....	82.5	.....	17.5	.....	21.5	.....	432.0	.....	Fairly fine; ferrite veins, slaggy areas
	6Y	48.0	.....	81.5	.....	17.5	.....	28.5	.....	.....	.....	
	6T	.....	50.0	.....	83.0	.....	16.5	.....	22.0	.....	.....	Ingotism
	6N	60.0	.....	87.5	.....	14.5	.....	22.0	.....	.....	.....	Fine; trace ferrite ghosts
	6Q	83.5	85.0	100.5	104.0	16.5	12.5	26.5	24.5	452.0	456.0	Very fine, pitted with holes
	6QQ	70.0	.....	92.0	.....	23.0	.....	44.0	.....	.....	.....	Do.
C, 0.22-0.25....	7N	38.0	.....	64.0	.....	35.5	.....	52.5	.....	.....	.....	Fine, uniform
	7Q	69.3	.....	95.4	.....	18.3	.....	39.2	.....	.....	.....	Very fine, sorbitic, ferrite
	7QQ	57.8	.....	79.0	.....	27.3	.....	47.7	.....	.....	.....	Very fine, all sorbitic

X—inner zone.
Y—outer zone.T—tangential.
N—normalized.Q—quenched and drawn.
QQ—double-quenched and drawn.

5. MACROSTRUCTURE AND MICROSTRUCTURE

It is of interest to note there appeared no flaws or visible defects, other than small blowholes near the inner surface, in the preparation of any of the test pieces for physical or chemical examination. The blowholes noted were always within about one-sixteenth inch from the inner or free surface of the casting. No hard spots were found in any of the castings. Just next the inner surface of all castings there is a layer not over one-sixteenth inch thick which appears to contain nearly all the physical and chemical discontinuities.

Sulphur prints and cupric ammonium chloride etchings were made on transverse sections of each casting. Some of the sections photographed are shown on Figs. 3, 4, and 5, and represent the coarsest grained and most irregular portions of the sections

FIG. 3.—*Transverse sections of castings Nos. 1 and 5*

- (A) Casting No. 5: Nitric acid etching of a transverse section ($\times$, about $1\frac{1}{2}$). The structure is coarse grained with higher carbon areas in the inner zone
- (B) Casting No. 5: Sulphur print of a transverse section. There are small high-sulphur areas in the inner zone and several circumferential bands low in sulphur in the middle and outer zones
- (C) Casting No. 1: Cupric ammonium chloride etching of a transverse section. This structure is practically free from fir-tree crystals, but shows circumferential bands or zones apparently highest in carbon in the inner zone and lowest in carbon in the middle zone

FIG. 4.—*Portion of transverse ring from casting No. 4*

- (A) Sulphur print, actual size. There is little variation in the amount of sulphur, slightly more along inner edge than near outer edge. Several small local segregations may be seen
- (B) Cupric ammonium chloride etching ($\times 2$). This shows the coarse-grained structure of the steel

examined. The 72-inch longitudinal section was finished and rubbed down with fine emery paper, and a sulphur print was taken along the entire length; no longitudinal segregation was found.

FIG. 5.—Portion of transverse section of casting No. 7

- (A) Sulphur print, actual size. This shows practically no segregation of sulphur except a few small spots at the extreme inner edge where small surface blowholes occur.
- (B) Cupric ammonium chloride etching, actual size. This is a portion of the transverse section (full thickness of cylinder as cast, no machining) and shows the steel to be free from ingotism. There are small surface blowholes, all within $\frac{1}{16}$ inch of the surface. The inner zone (zone 3) is slightly higher in carbon.

At one point a hole or blister, 2 inches long, $\frac{1}{8}$ inch wide, was found $\frac{3}{8}$ inch from inside edge of the casting and a distance of 6 inches from one end. Fig. 3A, a nitric acid etching of the entire section,

revealed nothing that is not shown in the sulphur prints. Any appreciable segregation in the casting occurs transversely from outside to inside, as shown in the etched transverse section.

Specimens for microscopic examination were cut from transverse, radial (longitudinal), and tangential sections of each casting as received, and from transverse sections of the heat-treated bars; that is, after normalizing, quenching, and drawing, and double-quenching and drawing. Photomicrographs taken at a magnification of 50 diameters are shown and described in Figs. 4 to 9a. Each casting was found to contain relatively large ferrite areas (locally decarburized areas) or long ferrite veins (outlining very coarse primary crystals).

The most serious of the low-carbon areas were found in castings Nos. 3A and 6 (Figs. 7 and 8). These areas are not completely eliminated by normalizing, and persist even after quenching and drawing, but have been almost completely eliminated by the double-quench and draw treatment. The normalizing treatment, for the most part, greatly refines the structures, while quenching and drawing produces a sorbitic structure with partially diffused ferrite. Structures after the double-quench and draw compare favorably with those of large heat-treated steel forgings.

IV. SUMMARY

There were examined a miscellaneous lot of five castings in the form of cylinders of wall thickness $8\frac{1}{2}$ inches to $\frac{1}{2}$ inch, made by the Millsbaugh centrifugal process. Their composition ranged from two low-carbon steels, $C=0.17$ and 0.23 per cent, to three nickel steels ranging in carbon from $C=0.33$, 0.46 , to 0.66 per cent, and in nickel from $Ni=2.69$, 2.35 , to 2.92 per cent.

Segregation of the elements carbon, phosphorus, sulphur, nickel, and copper appears to exist to a slight extent, but only radially, and is most marked next the inner surface in a narrow zone of about one-sixteenth inch depth. Manganese and silicon do not segregate in this type of casting. The greatest carbon segregation was 0.09 per cent in nickel steel ($C=0.66$, $Ni=2.92$ per cent) and the least was 0.02 per cent in another nickel steel ($C=0.33$, $Ni=2.69$ per cent).

The *hardness* (Brinell and scleroscope) practically follows the segregation.

The only evidence of *unsoundness* was the presence of small blowholes in the inner zone, usually within one-sixteenth inch of surface.

A

B

FIG. 6.—Casting No. 5. Etched with picric acid. $\times 50$

(A) Transverse section. This steel is very coarse grained and apparently has not been annealed. The average structure consists of pearlite with a thin, polyhedral network of ferrite and is fairly uniform except the zone (about $\frac{1}{4}$ inch deep) adjacent to the bore, where there are large areas eutectoid in structure about 10 points higher in carbon than the average structure

(B) Radial, longitudinal section. This is similar to the transverse section

C

D

FIG. 6a.—Casting No. 5 as cast and normalized. Etched with picric acid.
× 50

- (C) Tangential section as cast. This structure is slightly finer than that of the transverse and radial sections (see Fig. 6)
- (D) Normalized. The grain has been greatly refined by this treatment, but traces of ferrite areas containing slag inclusions still remain. The ferrite network has not been entirely eliminated. A few small blowholes may be seen

FIG. 7.—Casting No. 6 as cast. Etched with picric acid. $\times 50$

- (A) Transverse section. This casting, although not annealed, has a fine-grained structure. Traces of fir-tree crystals are found near the inner edges, and coarse primary crystals are outlined by a thin ferrite network, but no slaggy ferrite areas appear in this section.
- (B) Radial section. This shows more pronounced fir-tree crystals than the transverse section.
- (C) Tangential section. A cluster of slaggy low-carbon areas appears in this section. Traces of fir-tree crystals were found also.

FIG. 8.—Casting No. 6 etched with picric acid. $\times 50$

- (A) Normalized. A fairly uniform, fine-grained ferrite-pearlite structure has been produced. No ferrite veins were found.
- (B) Water quenched and drawn. This structure is sorbitic with a fine network of undiffused ferrite. Slight traces of ferrite veins, partially broken up, were found.
- (C) Double-quenched and drawn. Although the structure has been greatly refined and the ferrite well diffused, shadowy traces of ferrite veins remain. An area pitted with tiny holes is here shown.

FIG. 9.—Casting No. 7 (basic open-hearth steel) etched with picric acid. $\times 50$

- (A) Transverse section, as received. There is a fine-grained uniform ferrite-pearlite structure free from blowholes, segregation, or slag. The steel has been well annealed
- (B) Radial (longitudinal) section as received. This structure is similar to that of the transverse section
- (C) Tangential section, as received. The structure is fine grained but has a few areas containing needle-like ferrite particles, indicating incomplete annealing

D

E

FIG. 9a.—Casting No. 7. *Transverse section etched with picric acid. $\times 50$*

(D) After single heat treatment. The steel has a very fine sorbitic structure with a ferrite network, and a few ferrite areas not fully broken up
(E) After double heat treatment. The structure is fine and sorbitic. The network has been broken up, but many ferrite areas still remain

The *density* across a section is practically constant; that is, to 0.004 in 7.836.

The *mechanical properties* show, in general, somewhat greater strength, elastic limit, and resistance to shock, but less ductility, in the tangential than in the longitudinal direction.

The *internal stresses* developed in the castings by this centrifugal process of manufacture, as determined from measurements on three rings from each of two castings, show values of the order of the elastic limit with the outer zones in compression.

The effect of *heat treatment* in improving the physical properties of the castings is very marked. The results suggest that the properties of such castings suitably treated may rival those of forgings of the same chemical composition.

The *microstructure* of at least some of these castings is better than that of ordinary castings; certain ones show pronounced ingotisms (dendritic structure). The nickel steels contain more slag inclusions than is usual in ordnance steel, showing that this centrifugal process may not clear up a basic steel. The ingotism and coarse grained structures of these centrifugal castings can, in general, be removed only by prolonged and repeated heat treatments; that is, normalizing followed by double-quench and draw.

The above account is limited to a description of the tests, and no references are given as to the details of the manufacturing operations, since we had no first-hand information concerning them.

Acknowledgments should be made to the members of the staff of the divisions of chemistry, structural materials, and metallurgy who assisted in these tests and in particular to G. N. Nauss, who followed them through in detail.

WASHINGTON, February 11, 1921.