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ELECTRIC-ARC WELDING OF STEEL:

I. PROPERTIES OF THE ARC-FUSED METAL

BY

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ELECTRIC-ARC WELDING OF STEEL: I. PROPERTIES OF THE ARC-FUSED METAL

By Henry S. Rawdon, Edward C. Groesbeck, and Louis Jordan

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I. INTRODUCTION

The daily advances in the variety and number of applications of electric welding bespeak the continually increasing industrial importance of this method of joining and repairing metals. Of the two forms of electric welding in common industrial use, the arc-fusion method is of far more general application than is electrical-resistance welding; arc welding, as is evident from its nature, can be applied in a multitude of ways to as many different welding projects, while the second method, which depends upon the contact resistance of the two parts which are to be joined together, finds its greatest applications in "repeat" welding.

Resistance welding is closely related to the familiar weld of the smith's forge in that the two surfaces to be joined are heated to the welding temperature, the electric current being the source of the necessary heat, and then pressed into intimate contact while

hot. The principle of arc welding, however, is very different; the two parts are joined together by fusion, the fused metal being supplied from an outside source rather than from the parts which are to be welded. Often the addition of a very considerable amount of metal is necessary, which metal is supplied by the fusion accomplished by means of the heat of the electric arc. A layer of considerable thickness often exists between the two parts joined together.

II. AIM OF THE INVESTIGATION

The application of arc welding in the shipbuilding industry is one of the most important and extensive applications which has as yet been proposed for this method. During the year 1918, at the request of and with the cooperation of the Welding Research Subcommittee of the Emergency Fleet Corporation, an extensive program was outlined by the Bureau of Standards for the study of this type of welding. The principal object of the research was to determine in an empirical way by actual welding tests carried out by skilled operators the relative values and merits of the different types of electrodes or welding pencils which are available commercially. Due to changed conditions, however, at the close of the year 1918 the original program was modified and shortened very considerably. The results of the investigation here given relate principally to the nature and characteristic properties of the weld, and in particular those of the "fused-in" metal.

In drawing up the modified program it was decided to make the study of the characteristic properties of the "fused-in" metal the primary object of the investigation, the study of the merits of the different types of electrodes being a secondary one. Since the metal of any weld produced by the electric-arc fusion method is essentially a casting because there is no refinement possible as in some of the other methods, it is apparent that the efficiency of the weld is dependent upon the properties of this arc-fused metal. Hence a knowledge of its properties is of fundamental importance in the study of electric-arc welds.

Though the results obtained throughout the entire series of examinations are not so conclusive as might be desired, it is believed that they contribute very materially to our knowledge of the properties of the "fused-in" metal, which conditions the serviceability of the electric-arc weld.

III. PRELIMINARY EXAMINATIONS OF ELECTRIC-ARC WELDS [1]

Numerous articles have appeared in the technical literature bearing on the subject of electric-arc welding. Most of these, however, are devoted to the technique and comparative merits of the method, manipulations, equipment, etc., rather than to the study of the characteristics of the metal of the weld itself. The information on this phase of the subject is rather meager.[2]

A considerable number of examinations was made of welds prepared by means of the electric-arc process and representative of different conditions of welding. Most of these were of a general miscellaneous nature, and the results do not warrant including a description of the different specimens here. One series of particular interest, however, may well be referred to in detail. As part of this study the Welding Research Subcommittee submitted to the Bureau of Standards for examination a number of welds of ship plate representative of English practice, some of the welds being considered as very superior examples of welding, others being of a decidedly inferior grade. In Tables 1 and 2 are given the results obtained by the mechanical tests made upon these specimens. The welding was done by skilled operators by means of special brands of electrodes (welding pencils), the trade names of which, however, have been omitted from the tables. In addition to the mechanical tests the specimens were examined very carefully microscopically. The results are not included, however, as the structural features of the material did not differ from those discussed later in Section VII. The results of the mechanical tests given are of value in that they are indicative of the average mechanical properties which should be expected in electric-arc welds of satisfactory grade and of the shape and size of those examined.

---

[1] These examinations, as well as the preparation of many of the specimens used later in the investigation, were made by B. Hurvitz, formerly assistant chemist of the Bureau of Standards.

[2] A fairly complete bibliography on the mechanical properties and structure of the metal of the weld and also on nitrogen in iron and steel has been given in the appendix. The necessary references throughout the text are made by quoting the bibliography title number.

TABLE 1.—Mechanical Properties of 12 Good Welds [a]

No.	Average voltage, direct current	Average current	Type of weld [b]	Thickness of plate	Ultimate tensile strength	Elongation	Gage length	Fracture
		Amperes		Inch	Lbs./in.^{2}	Per cent	Inches	
1	60	120	Vertical...	3/4	51 450	7	8	In weld, fine crystalline, some holes
2	60	120	...do.....	3/4	53 200	11	8	Do.
3	[c] 75	110	Flat.....	5/8	57 430	12	8	Outside weld, few holes.
4	[c] 75	110	...do.....	5/8	54 210	14	8	Do.
5	110	70	...do.....	1/4	60 610	5.5	6	Do.
6	110	125	...do.....	3/4	59 000	6	6	In weld, crystalline, fine to coarse, few holes
7	110	150	...do.....	1	52 570	6	6	In weld, very fine crystalline, few holes
8	110	100	Overhead .	1/2	59 470	4	6	In weld, fine crystalline, many holes
9	110	120	Flat.....	1/2	55 460	6	6	In weld, crystalline, fine to coarse, few holes
10	110	120	Vertical...	1/2	49 030	3.7	6	In weld, coarse crystalline, few holes
					Cold-bend test [d]			
					Load at yield	Load at break	Angle of bend	
					Pounds	Pounds	Degrees	
11	110	70	Flat.....	1/4	850	1 010	105	
12	110	150	...do.....	1	13 530	17 450	20	In weld, fine crystalline, few holes

[a] All the welds were made in steel plate of the thickness shown. Electrodes of the covered type were used. The welds were of 60° V type except the overhead welds, in which a 90° V was used.

[b] Refers to the position of the plates which were being welded together.

[c] Alternating current.

[d] The bend tests were made with the apex of V in tension with a 7-inch span over a pin of 2-inch radius except the ¼-inch plate, for which a pin of 1-inch radius was used.

TABLE 2.—Mechanical Properties of 12 Inferior Welds [a]

No.	Average voltage, direct current	Average current	Type of weld [b]	Thickness of plate	Ultimate tensile strength	Elongation	Gage length	Fracture
		Amperes		Inch	Lbs./in.²	Per cent	Inches	
13	110	120	Flat.....	5/8	32 460	Nil	.....	In weld, fine crystalline, many holes
14	95	105	Vertical...	1	19 890	Nil	.....	In weld, spongy metal, poor junction with metal of plate
15	95	105	Flat.....	1	31 700	.....	.....	Do.
16	60	120	...do.....	1/2	37 290	2	6	In weld, very fine grained with many holes
17	60	110	Vertical...	1/2	38 820	2	6	In weld, coarse crystalline, many holes
18	[c] 75	110	...do.....	7/8	31 360	Nil	.....	In weld, fine to coarse crystalline, many holes
19	[c] 75	110	...do.....	1	27 090	1.4	8	In weld, coarse crystalline, many holes
20	110	120	...do.....	1/2	39 400	3.5	6	In weld, very fine grained with crystalline areas, many holes
21	110	120	Flat.....	1/2	34 650	Nil	.....	In weld, very fine grained, very many holes
22	110	120	...do.....	3/4	35 120	Nil	.....	In weld, very fine to coarse crystalline, many holes
					Cold-bend test [d]			
					Load at yield	Load at break	Angle of bend	
					Pounds	Pounds	Degrees	
23	95	105	...do.....	1	4 930	4 930	Nil	In weld, very many laps and holes
24	95	105	Vertical...	1	4 120	4 610	1	Do.

[a] See note [a], Table 1. [b] See note [b], Table 1. [c] See note [c], Table 1. [d] See note [d], Table 1.

IV. METHOD AND MATERIALS [3]

The specimens required for the study of the mechanical properties of the arc-fused iron were prepared for the most part at this Bureau, direct current being used in the operation. The apparatus used is shown diagrammatically in Fig. 1. By means of the adjustable water rheostat the current could be regulated from 110 to 300 amperes. By the use of automatic recording instruments the voltage and current were measured and records were taken at intervals during the preparation of a specimen.

[3] Acknowledgement is due A. B. Engle, formerly laboratory assistant, for aid in the preparation of many of the specimens.

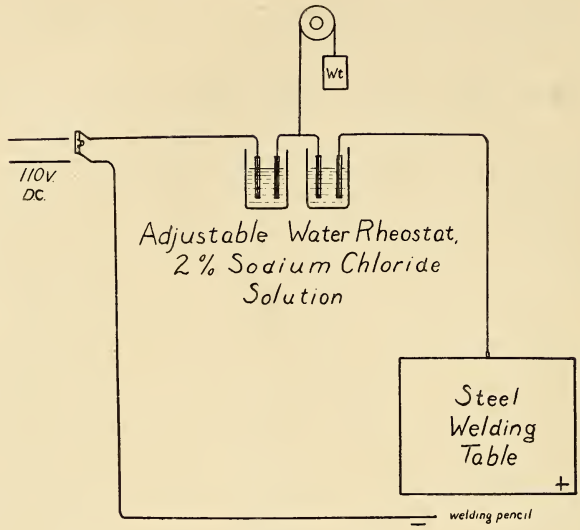

FIG. 1.—*Arrangement of apparatus for welding*

The values of current given below in the tables are those which were desired and were aimed at, the average deviation from the value as recorded by the curves being approximately ±5 amperes.

Since the investigation was concerned primarily with the properties of the arc-fused metal, regular welds were not made. Instead the metal was deposited in a block large enough to permit a tension specimen (0.505 inch diameter, 2-inch gage length) to be machined out of it. Although the opinion is held by some welders that the properties of the metal of an arc weld are affected materially by the adjacent metal by reason of the interpenetration of the two, it was decided that the change of properties of the added metal induced by fusion alone was of fundamental importance and should form the basis of any study of arc welding. The method adopted also permitted the use of larger specimens with much less machining than would have been possible had the metal been deposited in the usual form of a weld.

In the first few specimens prepared (10 in number) the metal was deposited by a series of "beadings" as shown in Fig. 2*a*. The tension specimens cut from the deposited metal were found to be very inferior and entirely unsuitable for the study. This was largely on account of the excessive overheating which occurred, as well as the fact that a relatively "long arc" was

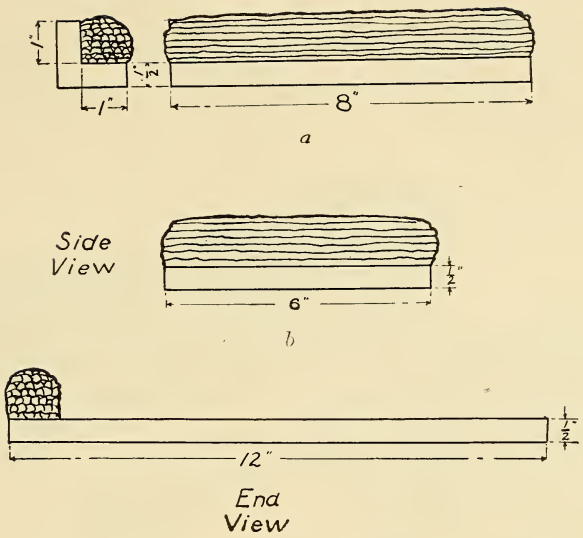

FIG. 2.—*Method of formation of the blocks of arc-fused steel*

a, Early method used, but discarded because of the inferiority of the resulting specimens; *b*, method used in the formation of all specimens, the results of which are given in the following pages

necessary for the fusion in this form. Because of the very evident inferiority of these specimens the results of the mechanical tests made are not given in the tables below (Sec. VI). The method of deposition of the metal was then changed to that shown in Fig. 2*b;* this method also had the advantage in that the amount of necessary machining for shaping the specimens for test was materially reduced. The block of arc-fused metal was built up on the end of a section of one-half inch plate of mild steel (ship plate) as shown. When a block of sufficient size had been formed, it, together with the portion of the steel plate immediately beneath, was sawed off from the remainder of the steel plate. The tension specimen was turned entirely out of the arc-fused metal. No difficulty whatever was experienced in machining the specimens. Fig. 3 shows the general appearance of the block of fused metal as well as the tension specimen turned out of it.

In general, in forming the blocks the fused metal was deposited as a series of "beads" so arranged that they were parallel to the axis of the tension specimen which was cut later from the block. In two cases for purposes of comparison the metal was deposited in "beads" at right angles to the length of the specimen. In all the specimens after the deposition of each layer the surface

was very carefully and vigorously brushed with a stiff wire brush to remove the layer of oxide and slag which formed during the fusion. There was found to be but little need to use the chisel for removing this layer.

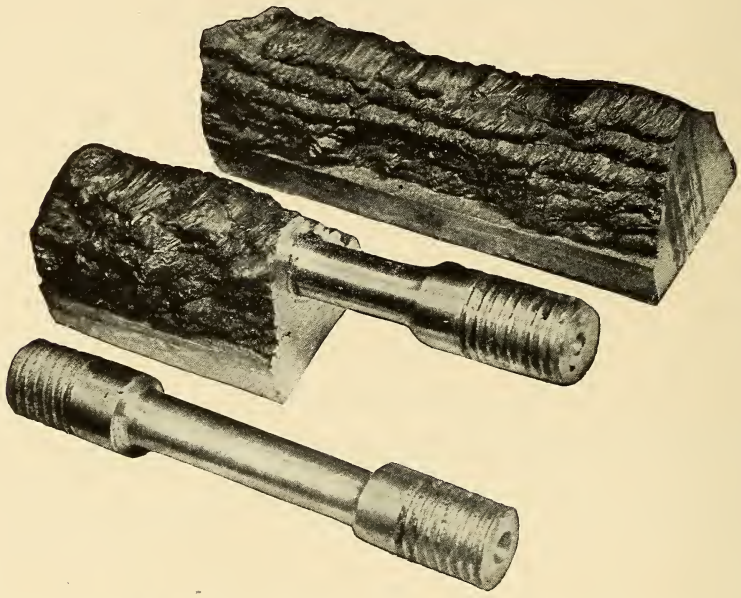

FIG. 3.—*Block of arc-fused metal with tension specimen cut from it. Reduction, approximately ½*

Two types of electrodes were used as material to be fused. These differed considerably in composition (Table 3, Sec. V) and were chosen as representative of a "pure" iron and a low-carbon steel. The two types will be referred to as "A" and "B," respectively, in the tables of results below. They were obtained in the following sizes: One-eighth inch, five-thirty-seconds inch, three-sixteenths inch, and one-fourth inch (A electrodes five-sixteenths inch). It was planned to use the different sizes with the following currents: One-fourth inch—75, 110, and 145 amperes; five-thirty-seconds inch—145, 185, and 225 amperes; three-sixteenths inch—185, 225, and 260 amperes; one-fourth inch (five-sixteenths inch)—300 amperes. The electrodes were used both in the bare condition and after being slightly coated with a deoxidizing and refractory mixture. For coating, a paste of the following composition was used: Fifteen g graphite, 7.5 g magnesium, 4 g aluminum, 65 g magnesium oxide, 60 g calcium oxide. To this mixture was added 120 cm^3 of sodium silicate (40° Be) and 150 cm^3 of water. The electrodes were painted on one side only with

the paste. The quantity given above was found to be sufficient for coating 500 electrodes. The purpose of the coating was to prevent excessive oxidation of the metal of the electrode during fusion and to form also a thin protective coating of slag upon the fused metal.

Tension specimens only were prepared from the arc-fused metal; the modification and curtailment of the original program rendered this necessary. It is quite generally recognized that the tension test falls very short in completely defining the mechanical properties of any metal; it is believed, however, that the behavior of this material when stressed in tension is so characteristic that its general behavior under other conditions of stress, particularly when subjected to the so-called dynamic tests—that is—vibration and shock, can be safely predicted from the results obtained. In order to supplement the specimens made at this Bureau a series of six was also prepared by one of the large manufacturers of equipment for electric welding to be included in the investigation. These are designated as "C" in the tables below.

V. CHANGES IN COMPOSITION OF ELECTRODES AS A RESULT OF FUSION [4]

In Table 3 below are given the results of the analyses of several typical specimens of the two types of electrodes used for welding and also results of analyses of similar material after arc-fusion.

TABLE 3.—Results of Chemical Analyses of Electrodes Before and After Fusion [a]

Electrode		Carbon		Silicon		Manganese		Phosphorus	
Type	Diameter	Before	After	Before	After	Before	After	Before	After
	Inch	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
A.....	1/8	0.058	0.046 [b] .031	0.33	0.007 [b] .007	0.042	Tr Tr	0.002	0.005 [b] .005
A.....	5/32	.....	.....	.....	.....	.....	.....	.....	.....
A.....	3/16	.022	.010 [b] .010 .033	.16	.012 [b] .014 .006	.038	Tr [b] Tr 0.069	.002	.003 [b] .002 .012
A.....	5/16	.....	.050	.....	.11	.....	.014	.....	.011
B.....	1/8	.15	..... .027 [b] .024	.06	..... .008 [b] .100	.47	..... Tr [b] Tr	.018	..... .002 [b] .004
B.....	5/32	.15	.....	.001	.....	.46	.....	.014	.....
B	3/16	.....	.....	.....	.....	.....	.....	.....	.....
B.....	1/4	.....	.....	.....	.....	.....	.....	.....	.....
C.....	5/32	.....	.....	.....	.....	.....	.....	.....	.....

[a] The electrodes which furnished the specimens used for analysis after fusion were not the identical ones used before fusion, but were the same stock.

[b] Results were obtained from the fusion of coated electrodes.

[4] Acknowledgment is due J. R. Cain, chemist, Bureau of Standards, for the method used in the determination of nitrogen. The details of the method, necessary precautions, and apparatus will be described in a separate publication.

TABLE 3.—Results of Chemical Analyses of Electrodes Before and After Fusion—Continued

Electrode		Sulphur		Copper [a]		Nitrogen [b]	
Type	Diameter	Before	After	Before	After	Before	After
	Inch	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
A	1/8	0.057	0.036 [c] .033	...	...	0.0030	0.156 .127 [c] .149 [c] .140
A	5/32	...	...	...	...	.0035	.140 .123 .124 [c] .121 [c] .119 [c] .113
A	3/16	.040	.033 [c] .035 .043	...	... ... 0.058	.0040	.126 .131 .133 [c] .127 [c] .131 [c] .134
A	5/16	...	.026	...	.063	.0037	.117 [c] .111
B	1/8	.021	... .035 [c] .035	...	...	.0032	.152 .132 [c] .141 [c] .135
B	5/32	.017	...	...	...	.0035	.124 .121 .117 [c] .122 [d] .132 [c] .123
B	3/16	...	...	...	...	.0022 .0025	.119 .111 .112 [c] .106 [c] .108 [c] .094
B	1/4	...	...	...	...	.0014 .0022	
C	5/32	...	...	...	...	...	.133 .098

[a] Determinations for copper were not carried out upon the unfused electrodes.

[b] Each of the results reported in the "after" fusion columns, excepting [e], is the average of two determinations made on one separate specimen.

[c] Results were obtained from the fusion of coated electrodes.

[d] Average of nine determinations.

It will be noted that the general effect of the fusion is to render the two materials more nearly the same in composition. The loss of carbon and of silicon is very marked in each case where these elements exist in considerable amounts. A similar tendency may be noted for manganese. The coating with which the electrodes were covered appears to have had but little influence, if any, in preventing the oxidation of the carbon and other elements.

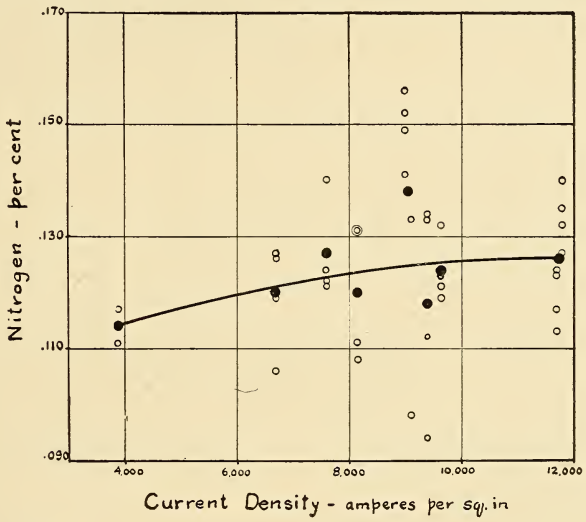

FIG. 4.—*Relation of current density to nitrogen content of the arc-fused steel*

The most noticeable change in composition is the increase in the nitrogen content of the metal. In general the increase was rather uniform for all specimens. In Table 4 are summarized the results of the nitrogen determinations together with the corresponding current density used for the fusion of the metal. In Fig. 4 the average nitrogen content found for the different conditions of fusion is plotted against the corresponding current density. Though no definite conclusion seems to be warranted, it may be said that, in general, the percentage of nitrogen taken up by the fused iron increases somewhat as the current density increases. With the lowest current densities used the amount of nitrogen was found to be appreciably less than for the higher current densities used. Paterson reports [3] an increase in nitrogen content under similar conditions.

TABLE 4.—Relation Between Nitrogen Content and Current Density

Diameter of electrode	Approximate current	Current density	Nitrogen content[a]			
			Specimen A	Specimen B	Specimen C	Average
	Amperes	Amp./in.^{2}	Per cent	Per cent	Per cent	Per cent
1/8 inch	110	9 000	0.156 [b] 149	0.152 [b] 141	.....	0.138
1/8 inch	145	11 800	.127 [b] 140	.132 [b] 135	.....	.126
5/32 inch	145	7 600	.140 [b] 121	.124 [b] 122	.....	.127
5/32 inch	185	9 650	.123 [b] 119	.121 [b,d] 132	.....	.131
5/32 inch	225	11 700	.124 [b] 113	.117 [b] 123	.....	([c])
5/32 inch	175	9 100	.....	.....	0.133 .098	([e])
3/16 inch	185	6 700	.126 [b] 127	.119 [b] 106	.....	.120
3/16 inch	225	8 150	.131 [b] 131	.111 [b] 108	.....	.120
3/16 inch	260	9 400	.133 [b] 134	.112 .094	.....	.118
5/16 inch	300	3 900	.117 [b] 111	.....	.....	.114

[a] Average of two determinations.
[b] Coated electrodes.
[c] Included in average for C–D, 11 800.
[d] Average of nine determinations.
[e] Included in average for C–D, 9000.

VI. MECHANICAL PROPERTIES OF THE ARC-FUSED METAL

The mechanical properties of the two types of electrodes used as determined by the tension test are summarized in Table 5 below.

TABLE 5.—Tensile Properties of Electrodes

Electrode		Proportional limit	Ultimate tensile strength	Elongation in 2 inches	Reduction of area
Type	Diameter				
	Inch	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
A	5/32	39 000	65 800	16.5	69.2
A	3/16	48 000	62 100	9.0	69.3
A	5/16	34 000	60 100	14.0	66.4
A	5/16	.....	57 300	15.5	67.6
B	5/32	67 000	88 600	4.5	51.3
B	3/16	58 500	84 700	7.0	59.8
B	1/4	37 500	66 300	15.0	61.4
B	1/4	.....	67 900	15.5	62.4

In Table 6 are given the results of the mechanical tests made upon the tension specimens which were turned out of the blocks of metal resulting from the fusion of the electrodes. For purposes of comparison the chemical composition of the material is also included in the table. The specimens listed C–1, C–2, ... C–6 are the six which were prepared outside the Bureau and submitted for purposes of comparison. It was stated that they were prepared from bare electrodes five thirty-seconds inch in diameter, of type B, containing 0.17 per cent carbon and 0.5 per cent manganese.

TABLE 6.—Tensile Properties and Results of Chemical Analyses of 54 Specimens of Weld Metal (0.505 Inch Diameter Standard Tension Bar Used)

Sample No.	Diameter of electrode	Direct current	Tensile properties			Elongation in 2 in.	Reduction of area	Hardness		C	Si	Mn	P	S	Cu	N_2
			Ultimate tensile strength	Yield point	Proportional limit			Brinell	Scleroscope							
	Inch	Amp.	Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent									
BARE ELECTRODES																
A-2	1/8	110	49 850	36 600	25 000	6.0	6.5	108	17.0	.....	.....	.....	.....	.....	.....	0.156
A-3	1/8	145	51 950	36 250	30 000	8.0	13.0	114	18.0	0.046	0.007	Tr	0.005	0.036	.....	.127
A-7	5/32	145	47 550	.....	.....	6.0	7.4	108	15.6	.....	.....	.....	.....	.....	.....	.140
A-8	5/32	185	48 100	.....	.....	8.0	8.7	104	16.2	.....	.....	.....	.....	.....	.....	.123
A-9	5/32	225	45 500	.....	.....	8.0	9.6	101	15.2	.....	.....	.....	.....	.....	.....	.124
A-4	3/16	185	50 600	33 750	29 500	5.5	13.5	105	16.2	.010	.012	Tr	.003	.033	.....	.126
A-5	3/16	225	49 150	36 250	22 000	7.0	10.0	102	16.4	.033	.006	0.069	.012	.043	0.058	.131
A-6	3/16	260	50 950	33 750	28 800	10.5	12.0	107	17.4	.....	.....	.....	.....	.....	.....	.133
A-10	5/16	300	46 670	.....	.....	12.0	11.9	104	16.2	.050	.11	.014	.011	.026	.063	.117
COVERED ELECTRODES																
AD-2	1/8	110	51 250	35 000	25 600	9.5	11.0	103	17.8	.....	.....	.....	.....	.....	.....	.149
AD-2 *a*	1/8	110	43 000	.....	23 000	5.0	9.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
AD-3	1/8	145	51 100	33 750	25 000	8.5	10.5	110	17.2	.031	.007	Tr	.005	.033	.....	.140
AD-3 *a*	1/8	145	46 250	.....	24 250	7.0	12.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
AD-7	5/32	145	41 750	.....	.....	6.0	6.6	99	17.4	.....	.....	.....	.....	.....	.....	.121
AD-7 *a*	5/32	145	46 950	.....	25 500	8.0	9.4	.....	.....	.....	.....	.....	.....	.....	.....	.....
AD-8	5/32	185	44 620	.....	.....	6.5	5.8	103	16.8	.....	.....	.....	.....	.....	.....	.119
AD-8 *a*	5/32	185	43 600	.....	23 250	6.5	9.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
AD-9	5/32	225	46 900	.....	.....	9.5	10.1	96	16.8	.....	.....	.....	.....	.....	.....	.113
AD-9 *a*	5/32	225	41 550	.....	25 500	5.0	6.5	.....	.....	.....	.....	.....	.....	.....	.....	.....
AD-4	3/16	185	51 200	35 000	30 000	10.5	10.5	101	17.2	.010	.014	Tr	.002	.035	.....	.127
AD-4 *a*	3/16	185	45 700	.....	25 500	8.5	11.5	.....	.....	.....	.....	.....	.....	.....	.....	.....

AD-5	3/16	225	48 600	35 000	30 000	7.0	10.0	96	16.2							.131
AD-5 [a]	3/16	225	46 250		23 750	11.5	12.0									
AD-6	3/16	260	47 500	34 500	31 500	9.0	9.0	97	14.6							.134
AD-6 [a]	3/16	260	50 700			8.0	2.8	105	13.6							
AD-10	5/16	300	45 900			8.5	11.5	98	15.4							.111
BARE ELECTRODES																
B-2	1/8	110	52 650	37 000	27 000	7.5	7.5	114	18.8							[b] .152
B-3	1/8	145	54 500	36 000	27 000	12.5	12.0	106	15.8	.027	.008	Tr	.002	.035		[b] .132
B-4	5/32	145	46 450	33 500	26 000	5.0	7.0	102	16.2							[b] .124
B-5	5/32	185	49 600	34 250	27 000	7.5	9.0	108	16.2							[b] .121
B-6	5/32	225	49 500	30 500	28 000	9.0	7.5	110	16.6							[b] .117
B-7	3/16	185	47 550		28 500	7.5	11.5	95	17.4							[b] .119
B-8	5/32	225	42 900		18 750	7.5	16.2	101	16.2							[b] .111
B-9	5/32	260	47 500		21 500	12.0	13.5	102	15.4							[b] .112
COVERED ELECTRODES																
BD-2	1/8	110	49 050	33 750	27 500	9.0	12.0	100	16.0							[b] .141
BD-2 [a]	1/8	110	44 400		20 000	6.5	9.4									
BD-3	1/8	145	52 100	34 300	30 500	12.5	16.0	116	16.0	.024	.010	Tr	.004	.035		[b] .135
BD-3 [a]	1/8	145	50 850		23 500	13.0	17.5									
BD-4	5/32	145	48 130	31 000	30 500	8.0	10.0	101	14.8							[b] .122
BD-4 [a]	5/32	145	41 750		21 000	6.0	9.5									
BD-5	5/32	185	49 086	31 730	29 000	12.5	13.0	97	16.0							[c] .132
BD-5 [a]	5/32	185	47 100		22 500	11.0	12.5									
BD-6	5/32	225	45 500	30 500	25 000	8.5	10.5	95	15.6							[b] .123
BD-7	3/16	185	49 950		24 500	11.5	21.5	98	16.8							[b] .106
BD-7 [a]	3/16	185	51 150		23 750	14.5	19.5									
BD-8	3/16	225	41 500		17 850	6.0	12.7	99	13.8							[b] .108
BD-8 [a] [d]	[d] 3/16	[d] 225	48 750		21 250	12.5	16.0									
BD-9	3/16	260	46 350		24 000	10.0	15.0	99	14.6							[b] .094

[a] Second test of duplicate specimen. [b] Average of two determinations. [c] Average of nine determinations. [d] Doubtful.

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TABLE 6.—Tensile Properties and Results of Chemical Analyses of 54 Specimens of Weld Metal (0.505 Inch Diameter Standard Tension Bar Used)—Continued

BARE ELECTRODES

Sample No.	Diameter of electrode	Direct current	Tensile properties			Elongation in 2 in.	Reduction of area	Hardness		C	Si	Mn	P	S	Cu	N_2
			Ultimate tensile strength	Yield point	Proportional limit			Brinell	Scleroscope							
	Inch	Amp.	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent									
C-1	5/32	175	48 650	32 650	23 000	12.0	19.1	.....	.....	.....	.....	.....	.....	.....	.....	.....
C-2	5/32	175	45 200	32 400	23 000	7.5	16.6	.....	.....	.....	.....	.....	.....	.....	.....	.....
C-3	5/32	175	49 720	32 650	25 000	9.0	13.6	.....	.....	.....	.....	.....	.....	.....	.....	.....
C-4	5/32	175	54 500	32 500	25 000	11.0	17.5	118	19.2	.....	.....	.....	.....	.....	.....	[b] 0.133
C-5	5/32	175	50 900	32 500	24 000	15,0	23.0	109	15.2	.....	.....	.....	.....	.....	.....	[b] 0.098
C-6	5/32	175	50 500	33 500	23 000	12.0	16.0	.....	.....	.....	.....	.....	.....	.....	.....	.....

[b] Average of two determinations.

As an aid for more readily comparing the mechanical properties of the two types of arc-fused metal A and B, the results have been grouped as given in Table 7.

TABLE 7.—Tensile Properties and Hardness of Specimens of Weld Metal Prepared by the Bureau (Arranged in Order of Amperage Used)

Current used, amperes [a]		Tensile properties							
		Ultimate tensile strength				Yield point			
		Electrode A [b]		Electrode B [b]		Electrode A		Electrode B	
		Bare	Covered	Bare	Covered	Bare	Covered	Bare	Covered
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²
110		49 850	51 250	52 650	49 050	36 600	35 000	37 000	33 750
		.....	[c] 43 000	.....	[c] 44 400	.....	.....	.....	.....
145	Series 1	51 950	51 000	54 500	52 100	36 250	36 750	36 000	34 300
		.....	[c] 46 250	.....	[c] 50 850	.....	.....	.....	.....
	Series 2	47 550	41 750	46 450	48 130	.....	.....	33 500	31 000
		.....	[c] 46 950	.....	[c] 41 750	.....	.....	.....	.....
185	Series 1	48 100	44 620	49 600	49 086	.....	.....	34 250	31 730
		.....	[c] 43 600	.....	[c] 47 100	.....	.....	.....	.....
	Series 2	50 600	51 200	47 550	49 950	33 750	35 000	.....	.....
		.....	[c] 45 700	.....	[c] 51 150	.....	.....	.....	.....
225	Series 1	45 500	46 900	49 500	45 500	.....	.....	30 500	30 500
		.....	[c] 41 550	.....	.....	.....	.....	.....	.....
	Series 2	49 150	48 600	42 900	41 500	36 250	35 000	.....	.....
		.....	[c] 46 250	.....	.....	.....	.....	.....	.....
260		50 950	47 500	47 500	46 350	33 750	34 500	.....	.....
		.....	[c] 50 700	.....	.....	.....	.....	.....	.....
300		46 670	45 900	.....	.....	.....	.....	.....	.....
Average		48 900	46 600	48 800	47 450	35 300	34 650	34 250	32 250
		47 400		47 980		35 000		33 250	

[a] Size of electrode used: One-eighth inch diameter, 110 amperes and 145 amperes (series 1); 5/32 inch diameter, 145 amperes (series 2), 185 amperes (series 1), and 225 amperes (series 1); 3/16 inch diameter, 185 amperes (series 2), 225 amperes (series 2), and 260 amperes; 5/16 inch diameter, 300 amperes.

[b] A and B refer to the two types of electrodes used (Table 3).

[c] Duplicate specimen.

TABLE 7.—Tensile Properties and Hardness of Specimens of Weld Metal Prepared by the Bureau (Arranged in Order of Amperage Used)—Continued

Current used, amperes		Tensile properties—Continued							
		Elongation in 2 inches				Reduction in area			
		Electrode A		Electrode B		Electrode A		Electrode B	
		Bare	Covered	Bare	Covered	Bare	Covered	Bare	Covered
		Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
110		6.0	9.5	7.5	9.0	6.5	11.0	7.5	12.0
		.....	[a] 5.0	.....	[a] 6.5	.....	[a] 9.0	.....	[a] 9.4
145	Series 1	8.0	8.5	12.5	12.5	13.0	10.5	12.0	16.0
		.....	[a] 7.0	.....	[a] 13.0	.....	[a] 12.0	.....	[a] 17.5
	Series 2	6.0	6.0	5.0	8.0	7.4	6.6	7.0	10.0
		.....	[a] 8.0	.....	[a] 6.0	.....	[a] 9.4	.....	[a] 9.5
185	Series 1	8.0	6.5	7.5	12.5	8.7	5.8	9.0	13.0
		.....	[a] 6.5	.....	[a] 11.0	.....	[a] 9.0	.....	[a] 12.5
	Series 2	5.5	10.5	7.5	11.5	23.5	10.5	11.5	21.5
		.....	[a] 8.5	.....	[a] 14.5	.....	[a] 11.5	.....	[a] 19.5
225	Series 1	8.0	9.5	9.0	8.5	9.6	10.1	7.5	10.5
		.....	[a] 5.0	.....	.....	.....	[a] 6.5	.....	.....
	Series 2	7.0	7.0	7.5	6.0	10.0	10.0	16.2	12.7
		.....	[a] 11.5	.....	.....	.....	[a] 12.0	.....	.....
260		10.5	9.0	12.0	10.0	12.0	9.0	13.5	15.0
		.....	[a] 8.0	.....	.....	.....	[a] 2.8	.....	.....
300		12.0	8.5	.....	.....	11.9	11.5	.....	.....
Average		7.9	8.5	8.5	9.9	10.3	9.2	10.5	13.8
		7.9		9.0		9.6		12.5	

Current used, amperes		Brinell and scleroscope hardness							
		Electrode A				Electrode B			
		Brinell		Scleroscope		Brinell		Scleroscope	
		Bare	Covered	Bare	Covered	Bare	Covered	Bare	Covered
110		108	103	17.0	17.8	114	100	18.8	16.0
		.....	.....	.....	.....	.....	.....	.....	.....
145	Series 1	114	110	18.0	17.2	106	116	15.8	16.0
		.....	.....	.....	.....	.....	.....	.....	.....
	Series 2	108	99	15.6	17.4	102	101	16.2	14.8
		.....	.....	.....	.....	.....	.....	.....	.....
185	Series 1	104	103	16.2	16.8	108	97	16.2	16.0
		.....	.....	.....	.....	.....	.....	.....	.....
	Series 2	105	101	16.2	17.2	95	98	17.4	16.8
		.....	.....	.....	.....	.....	.....	.....	.....
225	Series 1	101	96	15.2	16.8	110	95	16.6	15.6
		.....	.....	.....	.....	.....	.....	.....	.....
	Series 2	102	96	16.4	16.2	101	99	16.2	13.8
		.....	.....	.....	.....	.....	.....	.....	.....
260		107	97	17.4	14.6	102	99	15.4	14.6
		.....	.....	.....	.....	.....	.....	.....	.....
300		104	.....	16.2	.....	.....	.....	.....	.....
Average		106	100	16.5	16.8	105	101	16.6	15.5
		103		16.6		103		16.0	

[a] Duplicate specimen.

The characteristic appearance of specimens after testing, illustrating their behavior when stressed in tension until rupture occurs, is shown in Figs. 5, *a* and *b*. These represent two views

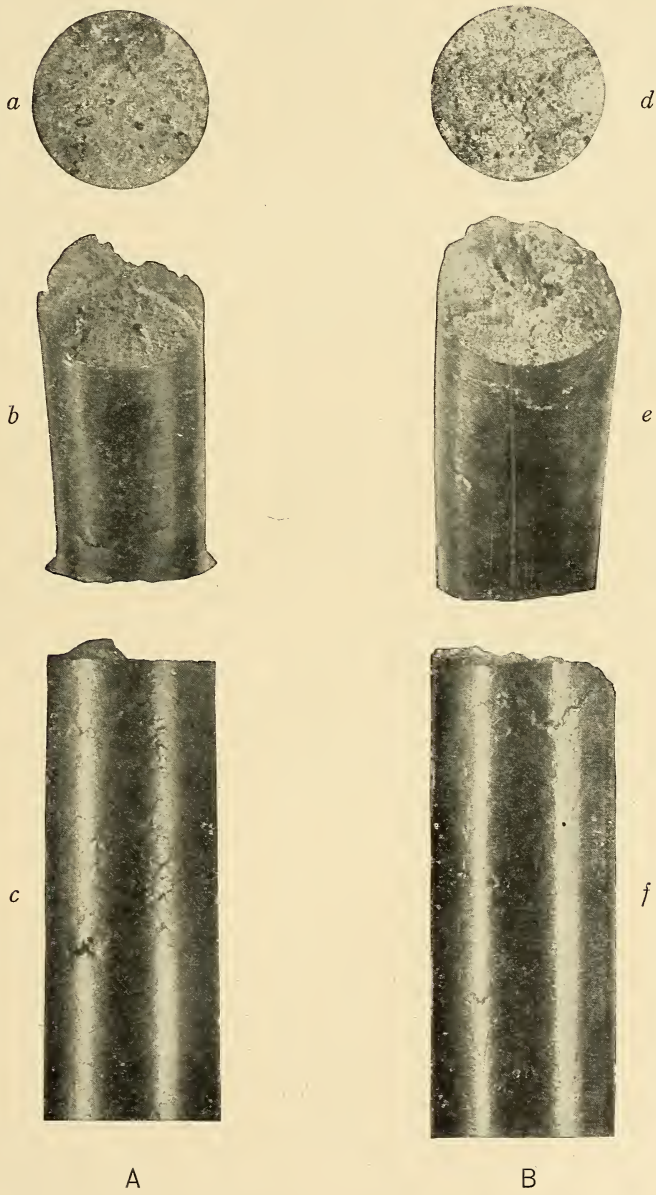


FIG. 5.—*Characteristic appearance of tension specimens after test.* × 2

A, specimen B-3 (Table 6); *B*, specimen BD-6 (Table 6); *a*, *d*, face of fracture, viewed normally; *b*, *e*, fractured end of specimen, viewed at an angle of 45°; *c*, *f*, side view of specimen

of the face of the fracture, one in which the line of vision is perpendicular to the face, the other at an angle of 45°, together with a side view of the cylindrical surface of the specimen. The features shown in Fig. 5 are characteristic of all the specimens tested, though in some they were much more pronounced than those shown. The fracture of the specimen in all cases reveals interior flaws. In some of the specimens, however, these are microscopic and of the character shown in Fig. 12. Although many of the specimens (from the results of Table 6) appear to have a considerable elongation, it is seen from Fig. 5 that the measured elongation does not truly represent a property of the metal itself. It is due rather to interior defects which indicate lack of perfect union of succeeding additions of metal during the process of fusion. The surface markings of the specimen after stressing to rupture are very similar to those seen in the familiar "flaky steel."

It appears from the results above that, as far as the mechanical properties are concerned, nothing was gained by coating the electrodes. The results show no decided superiority for either of the two types of electrodes used. This may be expected, however, when one considers that the two are rendered practically the same in composition during fusion by the burning out of the carbon and other elements.

The results of the tension tests upon the C series of specimens, which were made outside of this Bureau and submitted to be included in the investigation, show no marked difference between these samples and those prepared by this Bureau. In all cases the results obtained in the tension test are determined by the soundness of the metal and do not necessarily indicate the real mechanical properties of the material.

The results of the hardness determinations do not appear to have any particular or unusual significance. The variations are of the same general nature and relative magnitude as the variations observed in the results of the tension test. In general, the higher hardness number accompanies the higher tensile values, though this was not invariably so. As previously noted, specimens were prepared for the purpose of showing the relation between the direction in which the stress is applied and the manner of deposition of the metal. The metal was deposited in the form shown in Fig. 3, except that the "beads" extended across the piece rather than lengthwise, hence the "beads" of fused metal were at right angles to the direction in which the tensional stress

was applied. The results of the tension tests show that these two specimens (AW–1 and AW–2) were decidedly inferior to those prepared in the other manner, as shown in the table below.

TABLE 8.—Mechanical Properties of Arc-Fused Metal Deposited at Right Angles to Length of Specimen

Specimen	Proportional limit	Ultimate tensile strength	Elongation in 2 inches	Reduction of area
	Lbs./in.²	Lbs./in.²	Per cent	Per cent
AW–1	22 500	40 450	6.5	8.5
AW–2	22 500	39 500	4.0	3.0

VII. STRUCTURAL FEATURES: METALLOGRAPHIC EXAMINATION

1. MACROSTRUCTURE

The general condition of the metal resulting from the arc fusion is shown in Figs. 6 and 7, which show longitudinal medial sections of a series of the tension bars adjacent to the fractured end. The metal in all of these specimens was found to contain a considerable number of cavities and oxide inclusions; these are best seen after the surfaces are etched with a 10 per cent aqueous solution of copper-ammonium chloride. In many of the specimens the successive additions of metal are outlined by a series of very fine inclusions (probably oxide) which are revealed by the etching. There appears to be no definite relation between the soundness of the metal and the conditions of deposition—that is, for the range of current density used—nor does either type of electrode used show any decided superiority over the other with respect to porosity of the resulting fusion. In Fig. 8, *a* and *b*, is shown the appearance of a cross section of one of the blocks of arc-fused metal prepared outside of this Bureau by skilled welding operators. The condition of this material is quite similar to that prepared by this Bureau. The appearance of the fracture of one of the tension specimens made from such material is shown in Fig. 8*c*. The same defects as may be seen in the cross sections (Fig. 8, *a* and *b*) are also to be found on the fractured end of the bar; in addition to these, there appears to be a seam of unwelded metal.

The later microscopic study of the material also revealed further evidence of unsoundness in all the three types, A, B, and C.

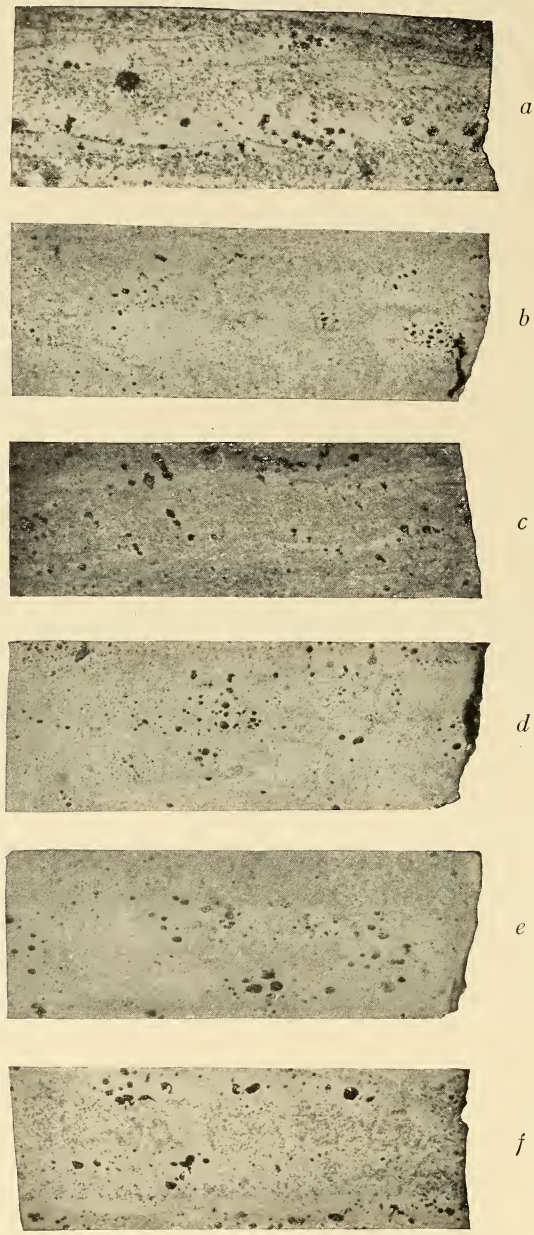


FIG. 6.—*Macrostructure of arc-fused metal from electrodes of type A.* × 2

Medial longitudinal sections of tension specimens (Table 6) were etched with 10 per cent aqueous solution of copper ammonium chloride. *a*, specimen AD-6, $\frac{3}{16}$-inch covered electrode, 260 amperes; *b*, specimen A-5, $\frac{3}{16}$-inch bare electrode, 225 amperes; *c*, specimen A-6, $\frac{3}{16}$-inch bare electrode, 260 amperes; *d*, specimen A-3, ⅛-inch bare electrode, 145 amperes; *e*, specimen A-4, $\frac{3}{16}$-inch bare electrode, 185 amperes; *f*, specimen AD-2, ⅛-inch covered electrode, 110 amperes

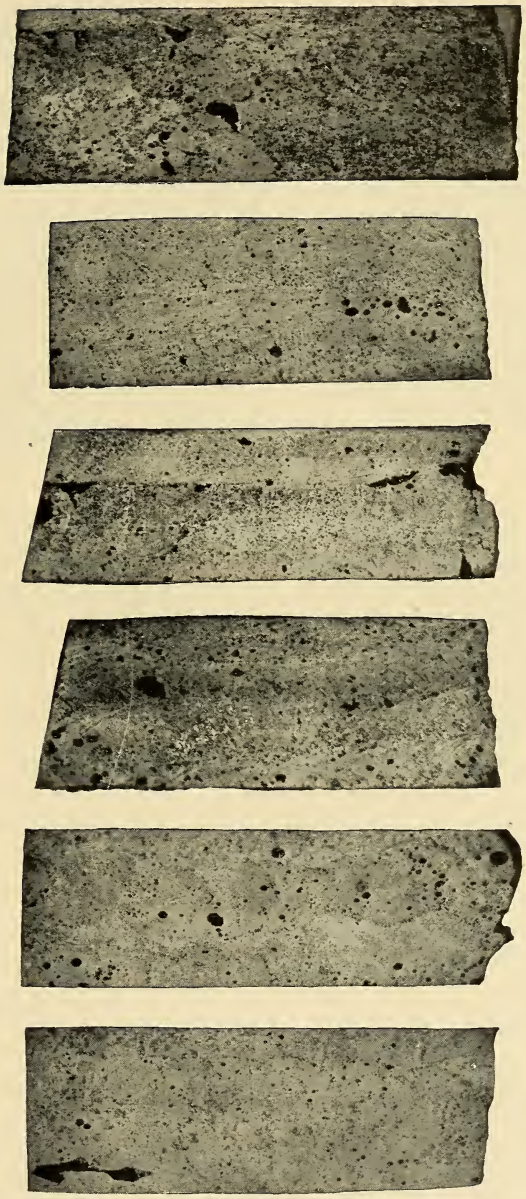


FIG. 7.—*Macrostructure of arc-fused metal from electrodes of type B.* × 2

Medial longitudinal sections of tension specimens (Table 6) were etched with 10 per cent aqueous solution of copper ammonium chloride. *a*, specimen B-4, $\frac{5}{32}$-inch bare electrode, 145 amperes; *b*, specimen B-5, $\frac{5}{32}$-inch bare electrode, 185 amperes; *c*, specimen B-3, $\frac{1}{8}$-inch bare electrode, 110 amperes; *d*, specimen B-3, $\frac{1}{8}$-inch bare electrode, 145 amperes; *e*, specimen BD-6, $\frac{5}{32}$-inch covered electrode, 225 amperes; *f*, specimen BD-4, $\frac{5}{32}$-inch covered electrode, 145 amperes

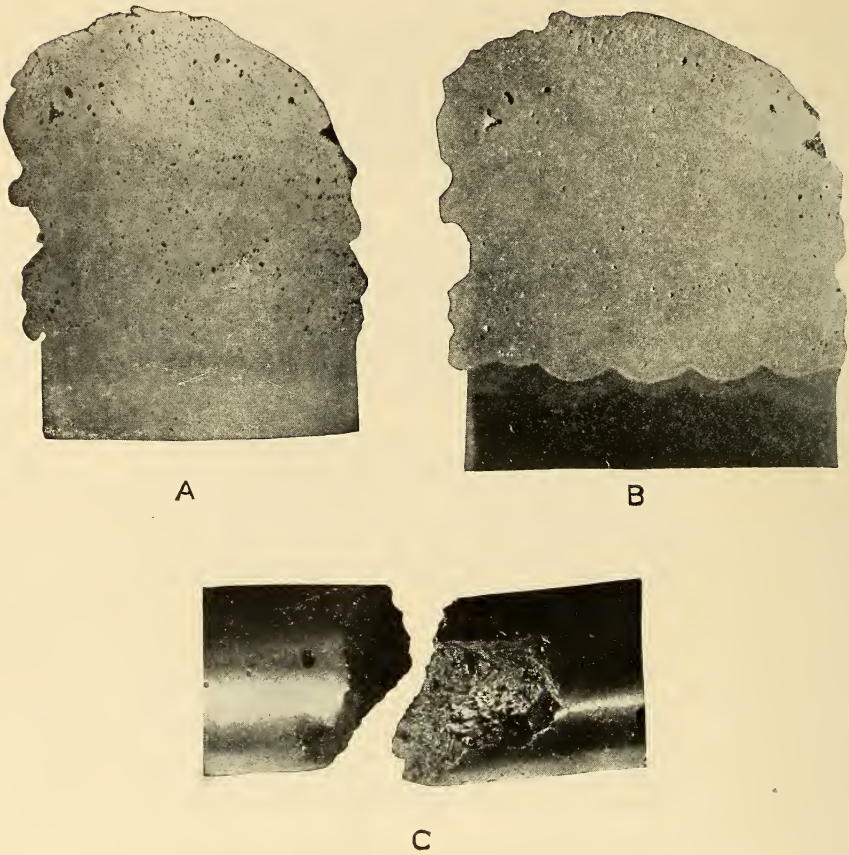


FIG. 8.—*Macrostructure of arc-fused metal, Type C*

A, cross section of the block of arc-fused metal from which specimen C-1 (Table 6) was turned; unetched, × 1; *B*, same as *A*, etched with 10 per cent aqueous solution of copper ammonium chloride, × 1.2; *C*, appearance of fractured tension specimen C-4 (Table 6), × 2

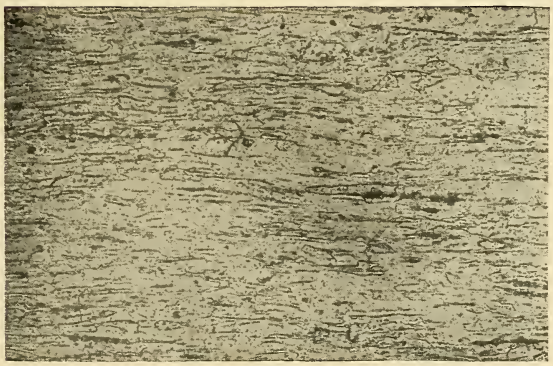
2. MICROSTRUCTURE

(*a*) GENERAL FEATURES.—For purposes of comparison the microstructure of the electrodes before fusion is shown in FIG. 9. The A electrodes have the appearance of steel of a very low carbon content. In some cases they were in the cold-rolled state; all showed a considerable number of inclusions. The B electrodes have the structure of a mild steel and are much freer from inclusions than are those of the other type. It is undoubtedly true, however, that the condition of the arc-fused metal with respect to the number of inclusions is a result of the fusion rather than of the initial state of the metal.

It is to be expected that the microstructure of the material after fusion will be very considerably changed, since the metal

is then essentially the same as a casting. It has some features, however, which are not to be found in steel as ordinarily cast.

A



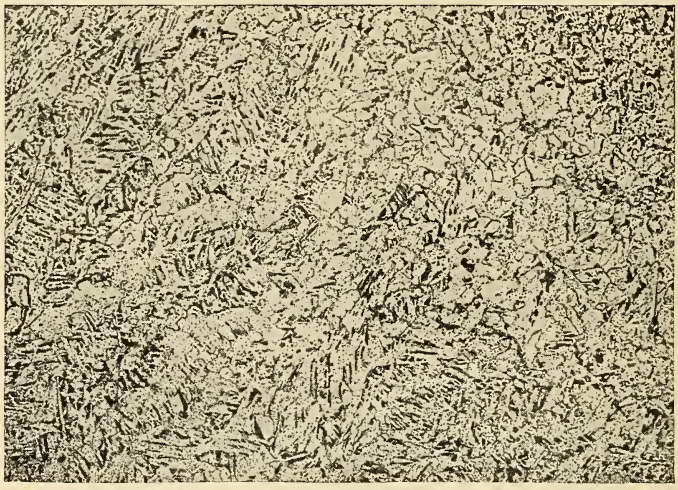
B

C

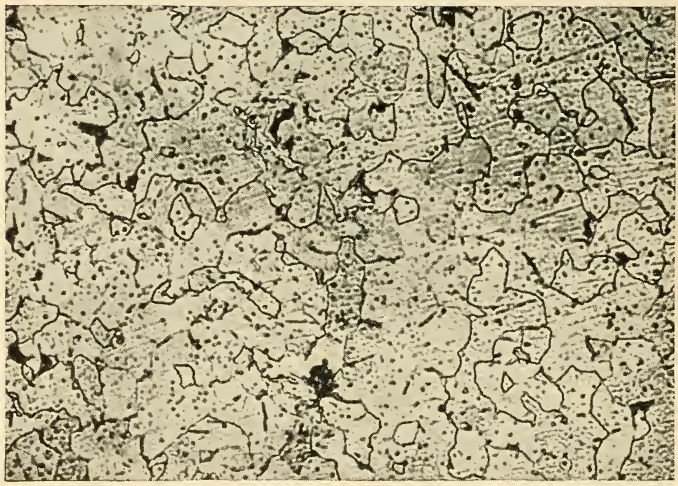
FIG. 9.—*Microstructure of electrodes before fusion.* × *100*

A, electrode of type A, $\frac{5}{32}$ inch, annealed as received; *B*, electrode of type B, ⅛ inch, cold drawn as received; *C*, electrode of type B, $\frac{3}{16}$ inch, annealed as received. Etching reagent, 5 per cent alcoholic solution of picric acid

The general type of microstructure was found to vary in the different specimens and to range from a condition which will be designated as "columnar" to that of a uniform fine equi-axed



A



B

FIG. 10.—*Typical microstructures of arc-fused metal, designated as "columnar" and "equiaxed."* × 100

A, columnar condition (specimen B-2, Table 6); etching reagents, 5 per cent alcoholic solution of picric acid; an equiaxed condition is shown in the upper right-hand corner; *B*, equiaxed condition (specimen AD-3, Table 6). Etching reagent, 2 per cent alcoholic solution of nitric acid

crystalline arrangement. This observation held true for both types of electrodes, whether bare or covered. Fig. 10 shows the

two extremes of microstructure which were found. In the examination of cross sections of the blocks of arc-fused metal, it was noticed that the equi-axed type of structure is prevalent throughout the interior of the piece and the columnar is to be found generally nearer the surface; that is, in the metal deposited last. It may be inferred from this that the metal of the layers which were deposited during the early part of the preparation of the specimen is refined considerably by the successive heatings to which it is subjected as additional layers of metal are deposited.

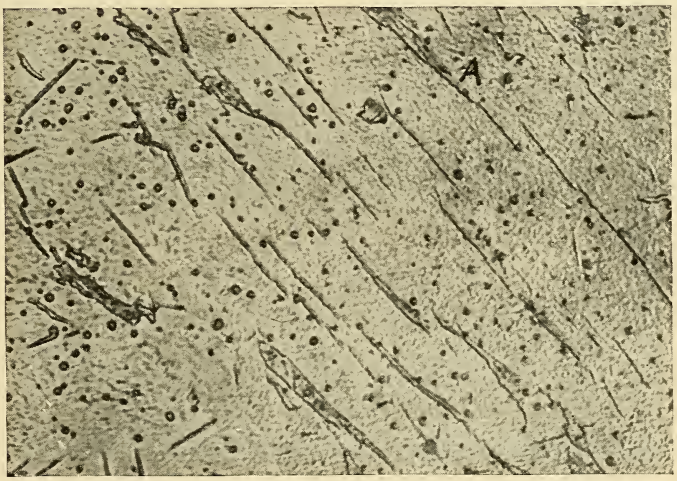


FIG. 11.—*Microstructure of arc-fused steel showing characteristic features, pearlite islands, "needles," and oxide inclusions.* × 750

The specimen (AD–2, Table 6) was etched with 2 per cent alcoholic solution of nitric acid

The general type of structure of the tension bars cut from the blocks of arc-fused metal will vary considerably according to the amount of refining which has taken place as well as the relative position of the tension specimen within the block. In addition it was noticed that the columnar and coarse equi-axed crystalline condition appears to predominate with fusion at high current densities.

(*b*) MICROSCOPIC EVIDENCE OF UNSOUNDNESS.—In all of the specimens of arc-fused metal examined microscopically there appear to be numerous tiny globules, apparently oxide, as shown in Figs. 10, 11, 12, and 13. A magnification of 500 diameters is usually necessary to show these inclusions. In general, they appear to have no definite arrangement but occur indiscriminately throughout the crystals of iron.

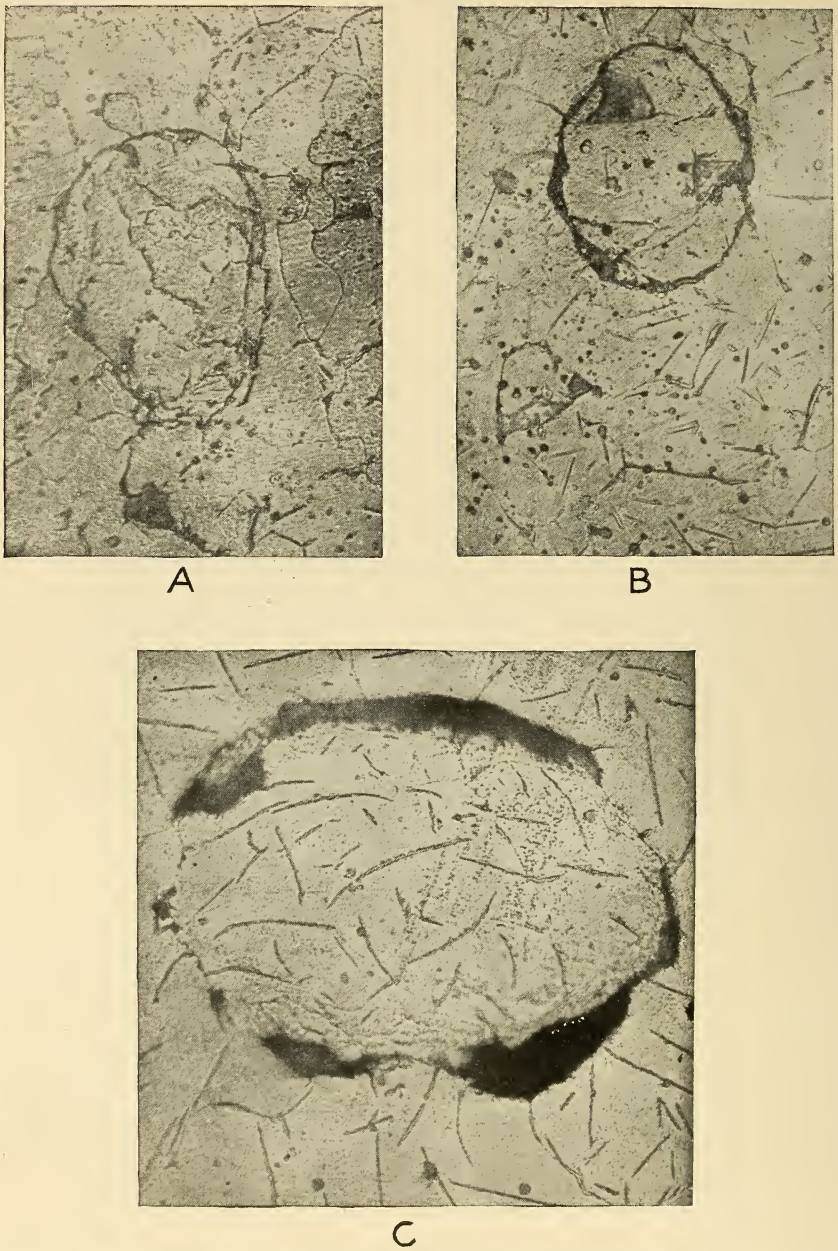


FIG. 12.—*Microstructure of arc-fused steel showing characteristic feature of "metallic-globule" inclusions.* × 500

A, specimen AD-9 (Table 6); *B*, specimen AD-10 (Table 6); *C*, specimen A-10 (Table 6) after heating 6 hours in vacuo. Etching reagent, 2 per cent alcoholic solution of nitric acid

A type of unsoundness frequently found is that shown in Fig. 12; this will be referred to as "metallic-globule inclusions." In

general, these globules possess a microstructure similar to that of the surrounding metal, but are enveloped by a film, presumably of oxide. It seems probable that they are small metallic particles which were formed as a sort of spray at the tip of the electrode and which were deposited on the solidified crust surrounding the pool of molten metal directly under the arc. These solidified particles apparently are not fused in with the metal which is subsequently deposited over them; that is, during the formation of this same layer and before any brushing of the surface occurs. By taking extreme precautions during the fusion a great deal of the unsoundness may be avoided, and the mechanical properties of the metal may be considerably improved. However, the specimens as described are more representative of actual present practice in welding.

(*c*) Characteristic "Needles" or "Plates."—The most characteristic feature of the steel after fusion is the presence of numerous lines or needles within the crystals. The general appearance of this feature of the structure is shown in Fig. 13. The number and the distribution of these "needles" were found to vary greatly in the different specimens. They are most abundant in the columnar and in the coarse equi-axed crystals. The finer equi-axed crystals in some specimens were found to be quite free from them, although exceptions were found to this rule. In general, a needle lies entirely within the bounds of an individual crystal. Some instances were found, however, where a needle appears to lie across the boundary and so lies within two adjacent crystals. Several instances of this tendency have been noted in the literature on this subject ([12]—Fig. 8; [27]—Fig. 30; [18]—p. 251, Fig. 14 B). The needles have an appreciable width, and, when the specimen is etched with 2 per cent alcoholic nitric acid, they appear much the same as cementite; that is, they remain uncolored, although they may appear to widen and darken if the etching is prolonged considerably. The apparent widening is evidently due to the attack of the adjacent ferrite along the boundary line between the two. The tendency of the needles to darken when etched with a hot alkaline solution of sodium picrate as reported by Comstock [12] was confirmed. Fig. 13, *c* illustrates the appearance when etched in this manner. The needles are sometimes found in a rectangular grouping; that is, they form angles of 90° with one another. In other cases they appear to be arranged along the octahedral planes of the crystal;

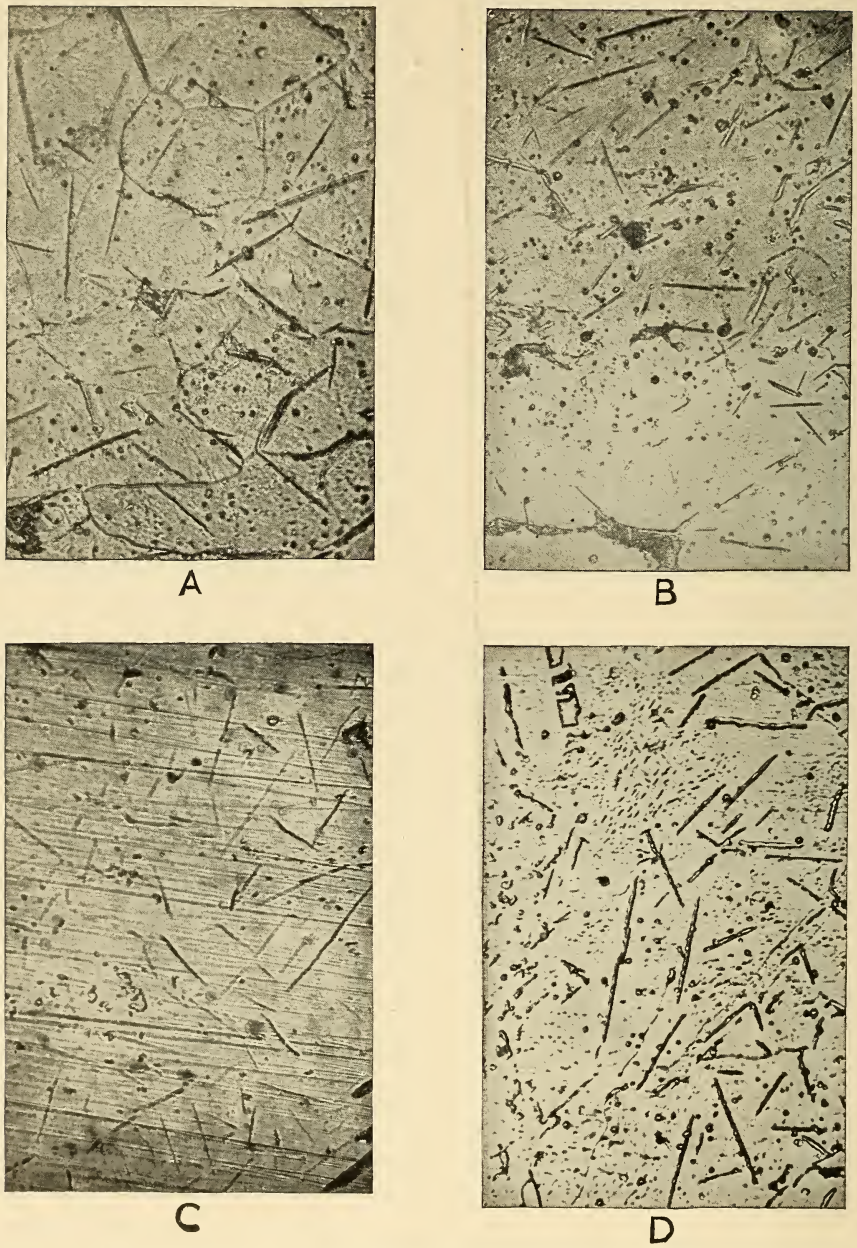


FIG. 13.—*Microstructure of arc-fused steel showing characteristic "needles" or "plates."* × 500

A, specimen BD (Table 6); *B*, specimen BD-3 (Table 6); *C*, specimen A-5 (Table 6) (the material was used for thermal analysis (Sec. VII, 4) and was heated to approximately 900 ° C four times and cooled in vacuo); *D*, specimen of welded ship plate, one of the specimens used in the preliminary examinations (sec. 3); in addition to the usual needles a second generation of very small ones may be seen. Etching reagents: *A* and *B*, 5 per cent alcoholic solution of picric acid; *C*, hot alkaline solution of sodium picrate; *D*, 2 per cent alcoholic solution of nitric acid

that is, at 60° to one another. This is best seen in specimens which have been heated as explained in section 3 below.

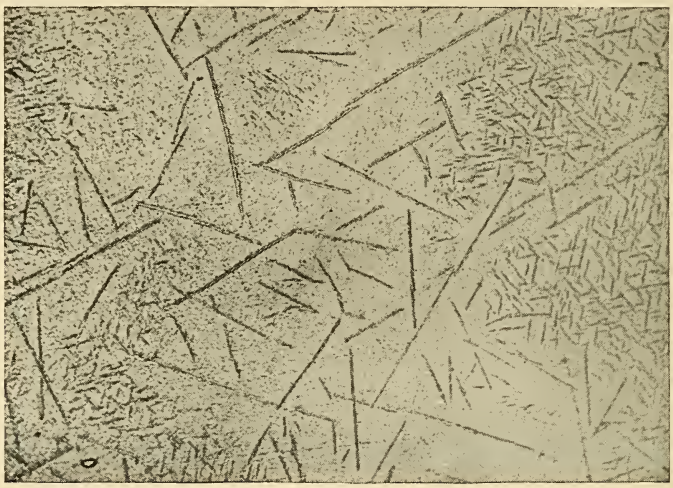
In some of the specimens certain crystals showed groups of very fine short needles (Fig. 13*d*). The needles comprising any one group or family are usually arranged parallel to one another, but the various groups are often arranged definitely with respect to one another in the same manner as described above. Similar needles have been reported in the literature by Miller [**14**].

An attempt was made [5] to determine whether the so-called lines or needles were really of the shape of needles or of tiny plates or scales. An area was carefully located on a specimen prepared for microscopic examination, which was then ground down slightly and repolished several times. It was possible to measure the amount of metal removed during the slight grinding by observing the gradual disappearance of certain of the spherical oxide inclusions the diameter of which could be accurately measured. By slightly etching the specimen after polishing anew it was possible to follow the gradual disappearance of some of the most prominent needles and to measure the maximum "depth" of such needles. It was concluded from the series of examinations that the term "plate" is more correctly descriptive of this feature of the structure than "line" or "needle." The thickness of the plate—that is, the width of the needle—varies from 0.0005 to 0.001 mm, and the width of the plate ("depth") may be as great as 0.005 mm. The persistence of the plates after a regrinding of the surface used for microscopical examination may be noted in some of the micrographs given by Miller [**21**]. The authors are not aware, however, of any other attempt to determine the shape of these plates by actual measurements of their dimensions.

The usual explanation of the nature of these plates is that they are due to nitrogen which is taken up by the iron during its fusion. Other suggestions which have been offered previously attribute them to oxide of iron and to carbide. The suggestion concerning oxide may be dismissed with a few words. The plates are distinctly different from oxide in their form and their behavior upon heating. It is shown later (sec. 3) that the tiny oxide globules coalesce into larger ones upon prolonged heating in vacuo, the plates also increase in size and become much more distinct (Fig. 25, *b*, *d*, *f*). In no case, however, was any intermediate stage

[5] This was carried out by P. D. Merica, formerly physicist of the Bureau of Standards.

between the globular form and the plate produced such as would be expected if both were of the same chemical nature.



A

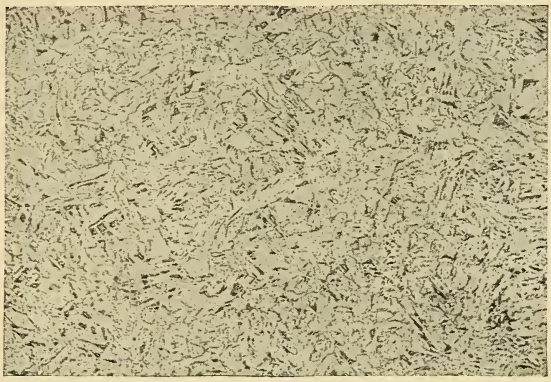
B

FIG. 14.—*Characteristic microstructure of "nitrogenized" iron.* × 500

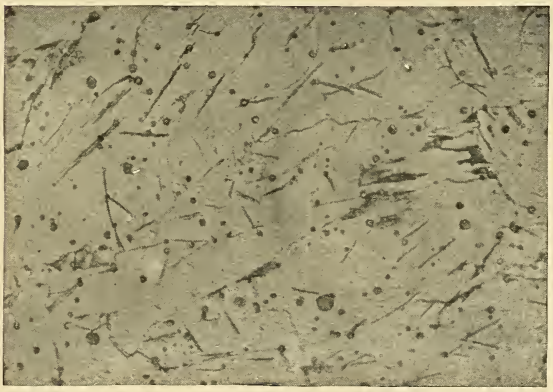
Electrolytic iron was heated for some hours at approximately 650° C in ammonia gas. It takes up nitrogen readily under these conditions. *A*, two types of needles occur, etching reagent, 2 per cent alcoholic nitric acid; *B*, same specimen as *A* (another area). Etching reagent, hot alkaline solution of sodium picrate

Regarding the assumption that they are cementite plates, it may be said that the tendency during fusion is for the carbon to be burnt out, thus leaving an iron of low carbon content. In all the

specimens islands of pearlite (usually with cementite borders) are to be found and may easily be distinguished with certainty. The number of such islands in any specimen appears to be sufficient to



A



B

FIG. 15.—*Microstructure of arc-fused steel produced in an atmosphere of carbon dioxide*

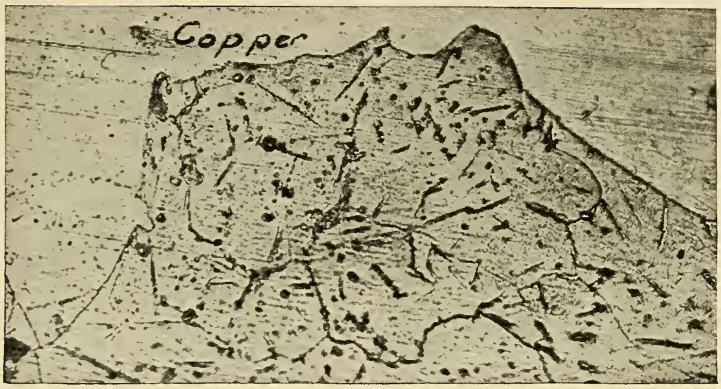
The structure is quite similar to that of the same fused in air; $\frac{5}{32}$-inch electrode of type A was used with 150 amperes. Etching reagent, 5 per cent alcoholic solution of picric acid; magnification, *A*, × 100; *B*, × 500

account for the carbon content of the material as revealed by chemical analysis. In some cases the pearlite islands are associated with a certain type of lines or needles such as are shown in Fig. 11. These needles, however, appear distinctly different from those of the prevailing type and are usually easily distinguished from them. The thermal analysis of arc-fused iron (Sec. VII, 4)

gives further evidence that the plates are not to be attributed to carbon.

The fact that the plates found in the arc-fused metal are identical in appearance and in behavior (for example, etching) as those found in iron which has been nitrogenized is strong evidence that both are of the same nature. Fig. 14*a* shows the appearance of the plates produced in electrolytic iron by heating it for some time in pure ammonia gas. These plates behave in the same characteristic manner when etched with sodium picrate as do those occurring in arc-fused iron (Fig. 14*b*). The fact that the nitrogen content of the steel is increased by the arc fusion also supports the view that the change which occurs in the structure is due to the nitrogen. The statement has been made by Ruder [**24**] that metal fused in the absence of nitrogen—that is, in an atmosphere of carbon dioxide or of hydrogen—does not contain any plates, and hence the view that the plates are due to the nitrogen is very much strengthened. In Fig. 15 the appearance of specimens prepared at this Bureau by arc fusion of electrodes of type A in an atmosphere of carbon dioxide is shown. The microscopic examination of the fused metal shows unmistakable evidence of the presence of some plates, although they differ somewhat from those found in nitrogenized iron and in metal fused in the air by the electric arc. Evidently they are due to a different cause from the majority of those formed in the iron fused in air. For convenience, in the remainder of the discussion the plates in the arc-fused metal will be referred to as "nitride plates."

(*d*) Relation of Microstructure to the Path of Rupture.—The faces of the fracture of several of the tension specimens after testing were heavily plated electrolytically with copper, so as to preserve the edges of the specimens during the polishing of the section, and examined microscopically to see if the course of the path of rupture had been influenced to an appreciable extent by the microstructural features. In general, the fracture appears to be intercrystalline in type. Along the path of rupture in all of the specimens were smooth-edged hollows, many of which had evidently been occupied by the "metallic globules" referred to above, while others were gas holes or pores. Portions of the fracture were intracrystalline and presented a jagged outline, but it can not be stated with certainty whether the needles have influenced the break at such points or not. Fig. 16 shows the appearance of some of the fractures and illus-



A

B

C

FIG. 16.—*Microstructure of arc-fused steel showing the relation of the path of rupture produced in tension to structural features.* × 500

A, Specimen B-4 (Table 6); *B*, same specimen as *A*, another spot; *C*, specimen B-6 (Table 6). The layer of copper indicated was deposited electrolytically on the fractured face of the specimen to protect it during polishing. Etching reagent, 2 per cent alcoholic solution of nitric acid

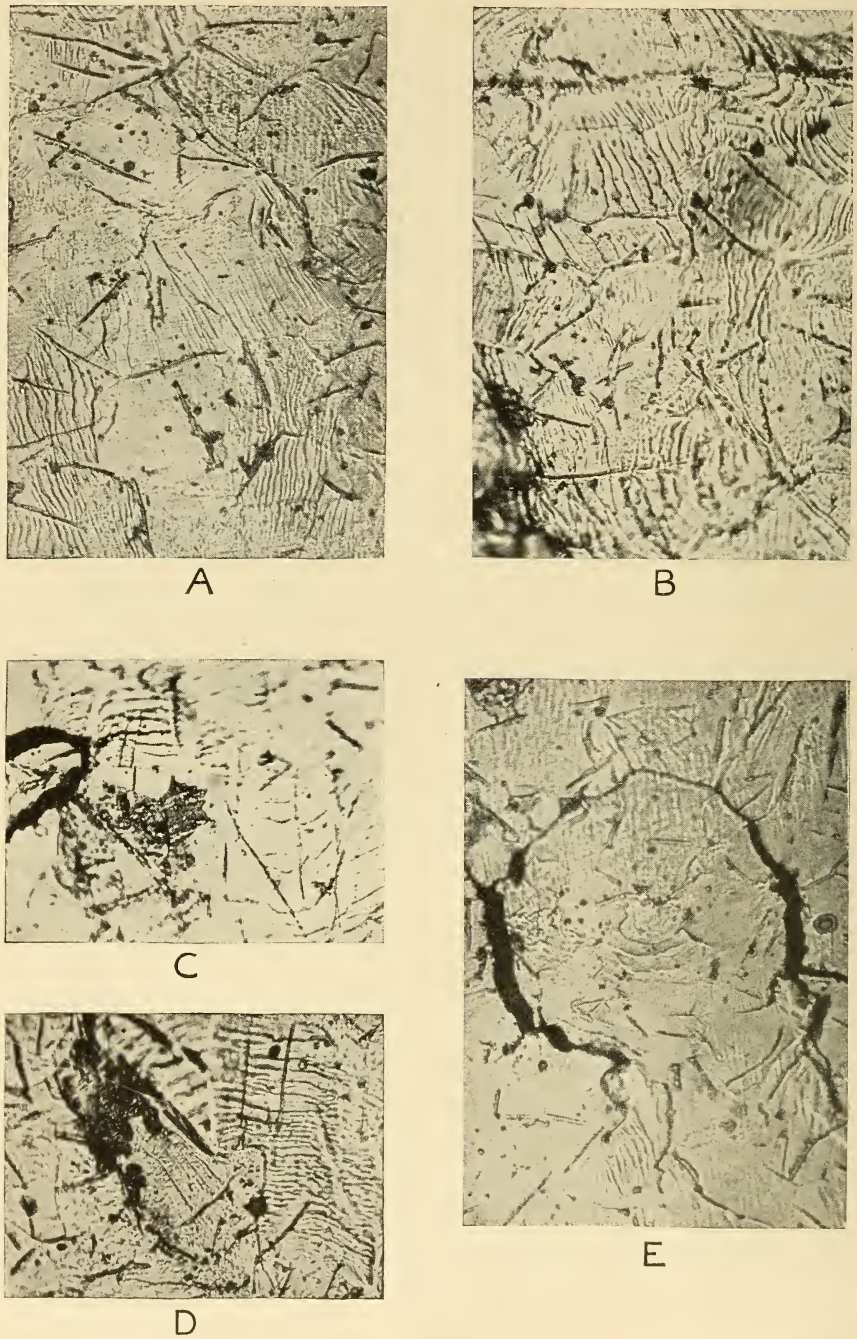


FIG. 17.—*Microstructure of arc-fused iron showing the behavior of "nitride plates" during plastic deformation of the metal.* × 500

A thin slice of specimen BD-2 (Table 6) was bent after polishing and etching with 2 per cent alcoholic nitric acid through an angle of 20° (approximate). *A* and *B* show that the "plates" have an effect upon the course of the slip bands similar to that of grain boundaries; that is, they cause a change of their direction; *C* and *D* show that a "faulting" of the "plates" sometimes occurs in grains which are very severely distorted; *E* shows that fracture upon bending usually starts in the oxide film inclosing "metallic globules" or in similar unsound areas

trates that, in general, the nitride plates do not appear to determine to any appreciable extent the course of the path of rupture.

The behavior of the plates under deformation can best be seen in thin specimens of the metal which were bent through a considerable angle. Results of examination of welds treated in this manner have been described by Miller [**14**]. Small rectangular plates of the arc-fused metal, approximately three thirty-seconds of an inch thick, were polished and etched for microscopic examination and were then bent in the vise through an angle of 20° (approximate).

In Fig. 17 are given micrographs illustrating the characteristic behavior of the material when subjected to bending. For moderate distortion the nitride plates influence the course of the slip bands in much the same way that grain boundaries do; that is, the slip bands terminate usually on meeting one of the plates with a change of direction so that they form a sharper angle with the plate than does the portion of the slip band which is at some distance away. When the deformation is greater, the slip bands occur on both sides of the nitride plate, but usually show a slight variation in direction on the two sides of the nitride plate; this is often quite pronounced at the point where the plate is crossed by the slip band. In a few cases evidence of the "faulting" of the plate as a result of severe distortion was noted. This was rare, however, because of the nature of the metal. On account of the inclusions and other features of unsoundness of the metal, rupture occurs at such points before the sound crystals have been sufficiently strained to show the characteristic behavior of the plates. Fig. 17*e* shows the beginning of a fracture around one of the metallic globule inclusions before the surrounding metal has been very severely strained. For this reason the influence of the plates on the mechanical properties of the crystals can not be stated with certainty. It would appear, however, that on account of the apparently unavoidable unsoundness of the metal, any possible influence of the nitride plates upon the mechanical properties of the material is quite negligible.

Some of the same specimens used for cold bending were torn partially in two after localizing the tear by means of a saw-cut in the edge of the plate. The specimen was then copper plated and prepared for microscopic examination, the surface having been ground away sufficiently to reveal the weld metal with the tear in it. Fig. 18 shows the appearance of the extreme end of a tear produced in this manner. The nitride plates do not appear to

have determined to any extent the path taken in the rupture produced in this manner.

3. EFFECT OF HEAT TREATMENT UPON STRUCTURE

With the view of possibly gaining further information as to the nature of the plates (assumed to be nitride) which constitute such a characteristic feature of the microstructure, a series of heat treatments was carried out upon several specimens of arc-fused electrodes of both types. Briefly stated, the treatment consisted in quenching the specimens in cold water after heating them for a period of 10 or 15 minutes at a temperature considerably above that of the Ac_3 transformation; 925°, 950°, and 1000° C were the temperatures used. After microscopical examination of the different quenched specimens they were tempered at different temperatures, which varied from 650 to 925° C for periods of 10 to 20 minutes. The samples which were used were rather small in size, being only one-eighth of an inch thick in order that the effect of the treatment should be very thorough,

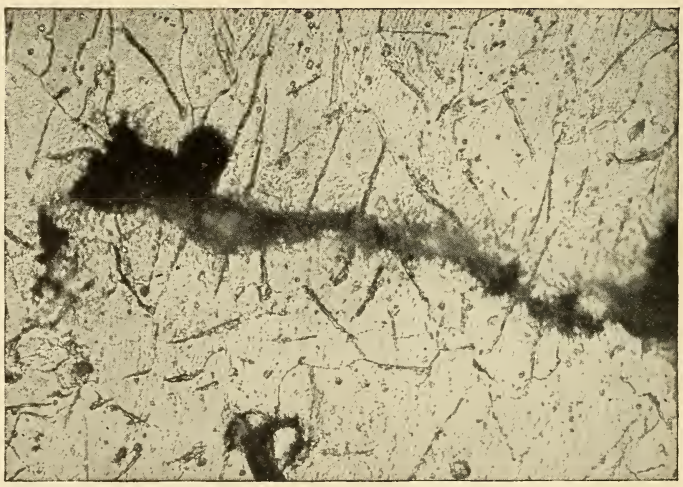


FIG. 18.—*Microstructure of arc-fused steel, showing the relation of the path of rupture to the "nitride plates."* × 500

A thin plate of metal (specimen of Fig. 17) was slowly torn after being partially sawed in two. The tear bears no evident relationship to the plates that lie in its path. Etching reagent used before fracturing the metal, 2 per cent alcoholic solution of nitric acid

and were taken from test bars A–2, A–6, AD–10, B–2, B–6, and B–9. These represented metal which had been deposited under different conditions of current density as shown in Table 6. No plates were found to be present in any of the specimens after quenching. Fig. 19 shows the appearance of one of the quenched

bars, which condition is typical of all. The structure indicates that the material comprising the plates had dissolved in the matrix of iron and had been retained in this condition upon quenching. The needlelike striations within the individual grains are characteristic of the condition resulting from the severe quenching and are to be observed at times in steel of a very low carbon content. Fig. 20 shows the appearance of one of the A electrodes (five thirty-seconds of an inch) quenched in cold water from 1000° C. Some of the crystals of the quenched iron also show interior markings somewhat similar in appearance to the nitride plates (Fig. 20*b*). These are, however, probably of the same nature as the interior treelike network sometimes seen in ferrite which has been heated to a high temperature.[6]

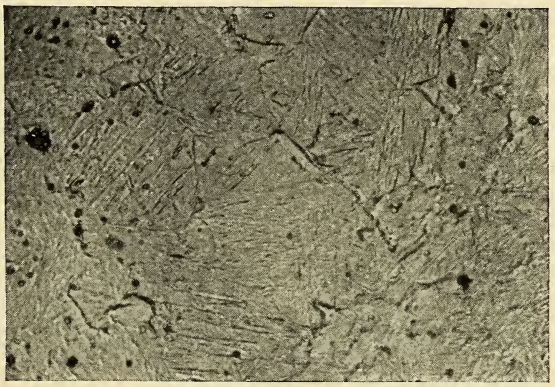


FIG. 19.—*Microstructure of arc-fused steel after quenching in water from 1000° C.* × 500

The plates characteristic of the material (specimen AD-10) before heating have disappeared and a martensitic pattern has been produced. Etching reagent, 5 per cent alcoholic solution of picric acid

The striations were found to be most pronounced in the specimens of arc-fused metal which were quenched from the highest temperatures, as might be expected. Braune **[49]** states that nitride of iron in quenched metal is retained in solution in the martensite. The same may be inferred from the statement by Giesen **[43]** "that in hardened steel, it (nitrogen) occurs in martensite." Ruder **[28]** has also shown that nitrogenized electrolytic iron (three hours at 700° C in ammonia), after being water quenched from a temperature of 600 to 950° C, shows none of the plates which were present before the specimen was heated.

[6] H. S. Rawdon and H. Scott, B. S. Sci. Papers, No. 356, Fig. 2*b*.

The sets of specimens (A–2, A–6, AD–10, B–2, B–6, and B–9) quenched from above the temperature of the Ac_3 transformation were heated to various temperatures, 650, 700, 800, and 925° C.

A

B

FIG. 20.—*Microstructure of "carbonless" steel after quenching in water from 1000° C. × 500*

A sample of electrode metal, type A, $\frac{1}{16}$ inch diameter, was used, being maintained 10 minutes at temperature before quenching. *A*, Some of the ferrite crystals (particularly near the surface of the specimen) show a faint pattern similar to that of Fig. 19; *B*, other ferrite crystals show interior markings somewhat suggestive of the plates of the arc-fused metal. Etching reagent, 2 per cent alcoholic solution of nitric acid

In all cases the specimens were maintained at the maximum temperature for approximately 10 to 15 minutes and then cooled in the furnace. Figs. 21 to 24, inclusive, summarize the resulting effects upon the structure. Heating to 650° C is not sufficient to allow the plates to redevelop, but in the specimens heated to 700° C a few small ones were found. The effect is progressively more pronounced with the increased temperature of tempering,

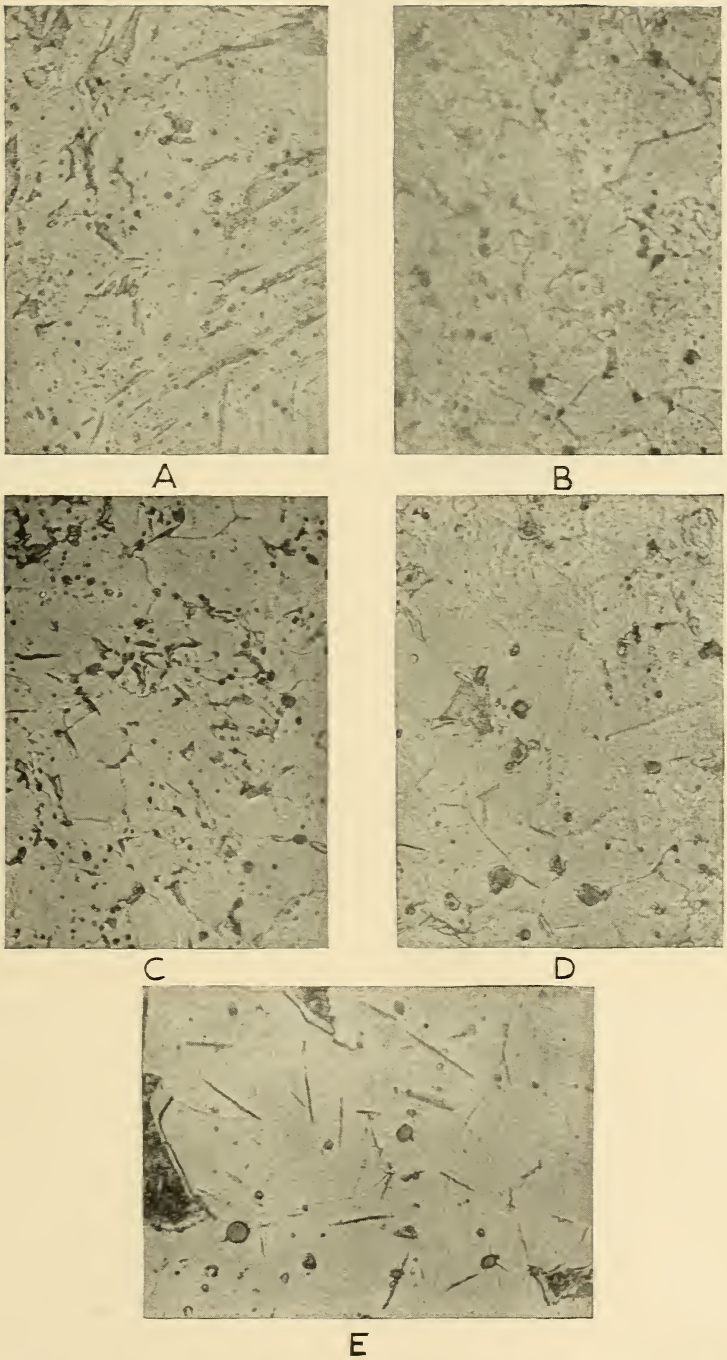


FIG. 21.—*Microstructure of arc-fused steel, Type A, showing the effect of heat treatment.* × 500

The specimen A-2 (Table 6) was quenched in water from approximately 1000° C (considerably above Ac_3 temperature, Fig. 27), and reheated as shown below. *A*, arc-fused metal as deposited; *B*, same as *A* after quenching and subsequently reheating to 650° C; no plates have formed during this treatment: *C*, a quenched specimen was reheated to 700° C; a few plates have appeared; *D*, a quenched specimen was reheated to 800° C; *E*, a quenched specimen was reheated to 925° C. Etching reagent, 2 per cent alcoholic solution of nitric acid

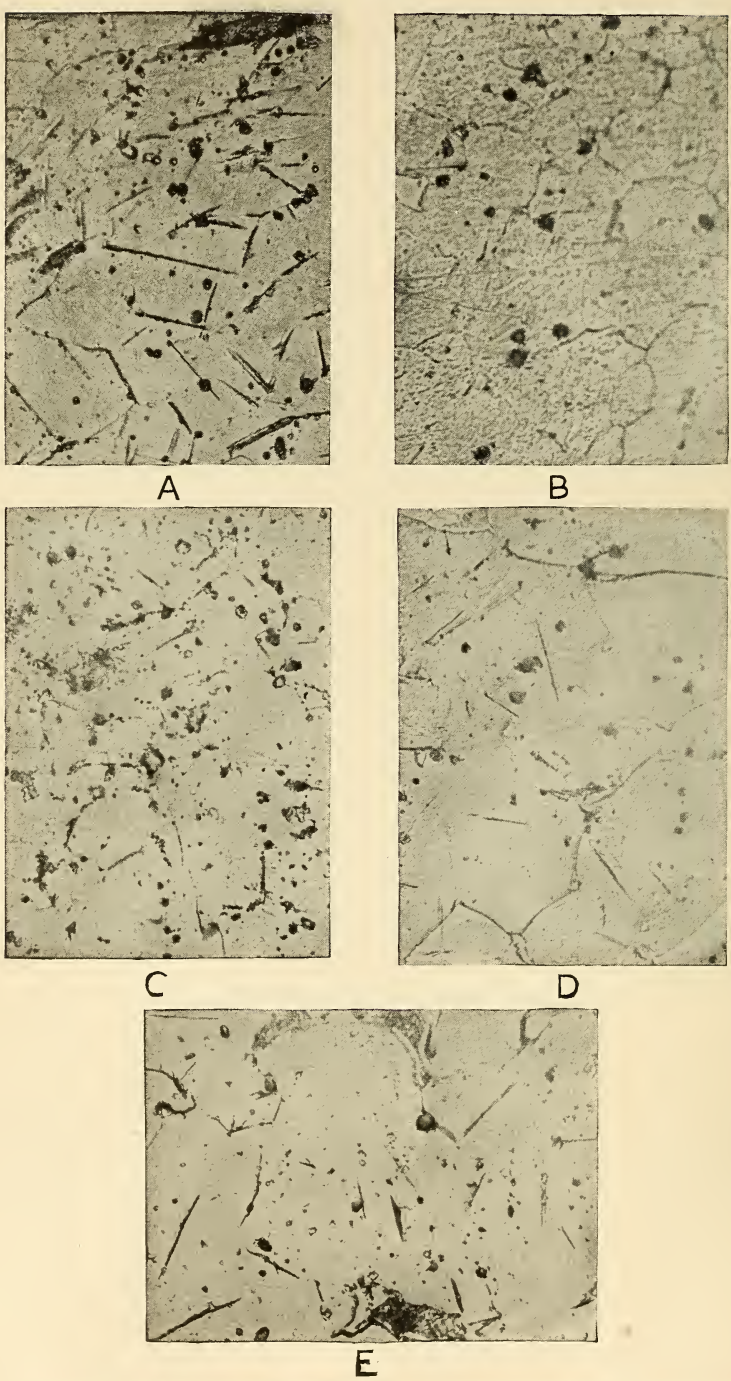


FIG. 22.—*Microstructure of arc-fused steel, type A, showing the effect of heat treatment.* × 500

The specimen AD-10 (Table 6) was quenched in water from approximately 1000° (C considerably above Ac_3 temperature, Fig. 27) and reheated as shown below. *A*, arc-fused metal as deposited; *B*, same as *A* after quenching and subsequently reheating to 650° C; no "plates" have been formed by this treatment; *C*, a quenched specimen was reheated to 700° C; a few plates have appeared; *D*, a quenched specimen was reheated to 800° C; *E*, a quenched specimen was reheated to 925° C. Etching reagent, 2 per cent alcoholic solution of nitric acid

and in the material heated to 925° C they are as large and as numerous as in any of the arc-fused specimens. The heating also develops the islands of pearlite, which are not always to be distinguished very clearly in the simple fused metal. The work of Ruder [28], referred to above, shows that nitrogenized iron which has been quenched and so rendered free from the nitride plates behaves in a similar manner upon heating to temperatures varying from 700 to 950° C; the plates reappear after a heating for 15 minutes at 700° C (or above), followed by a slow cooling. The similarity in behavior of the two is a further line of evidence that the arc-fused metal contains more or less nitrogenized iron throughout its mass.

The persistence of the nitride plates was also studied in specimens heated at 1000° C in vacuo for periods of six and of four and one-half hours. A set of specimens (one each of test bars A–D2, A–3, AD–6, A–10, B–2, B–4, B–5, and BD–5) was packed in a Usalite crucible, and covered with alundum "sand"; this crucible was surrounded by a protecting alundum tube and the whole heated in an Arsem furnace. A vacuum equivalent to 0.2 mm mercury was maintained for the greater part of the six-hour heating period; for the remainder of the time the vacuum was equivalent to 1.0 to 0.2 mm mercury. The specimens were allowed to cool in the furnace. Ruder [24] has stated that one hour's heating in vacuo at 1000° C was sufficient to cause a marked diminution in the number of plates in both arc-weld material and nitrogenized iron, and that at 1200° C they disappeared entirely.

The results obtained are shown in Fig. 25. In contradistinction to Ruder's work, the plates are more conspicuous and larger than before, and the oxide specks are larger and fewer in number. It would appear that the conditions of the experiment are favorable for a migration of the oxide through an appreciable distance and for a coalescing into larger masses. The oxide is eliminated entirely in a surface layer averaging approximately 0.15 mm in depth. Only in projections (right-angled corners, sections of threads of the tension bar, etc.) was there any removal of the nitride plates by the action of the continued heating in vacuo. This is shown in Fig. 26*c*, which illustrates the removal of the oxide inclusions also. No evidence was found that the small amount of carbon present in the arc-fused metal is eliminated, particularly very far beneath the surface.

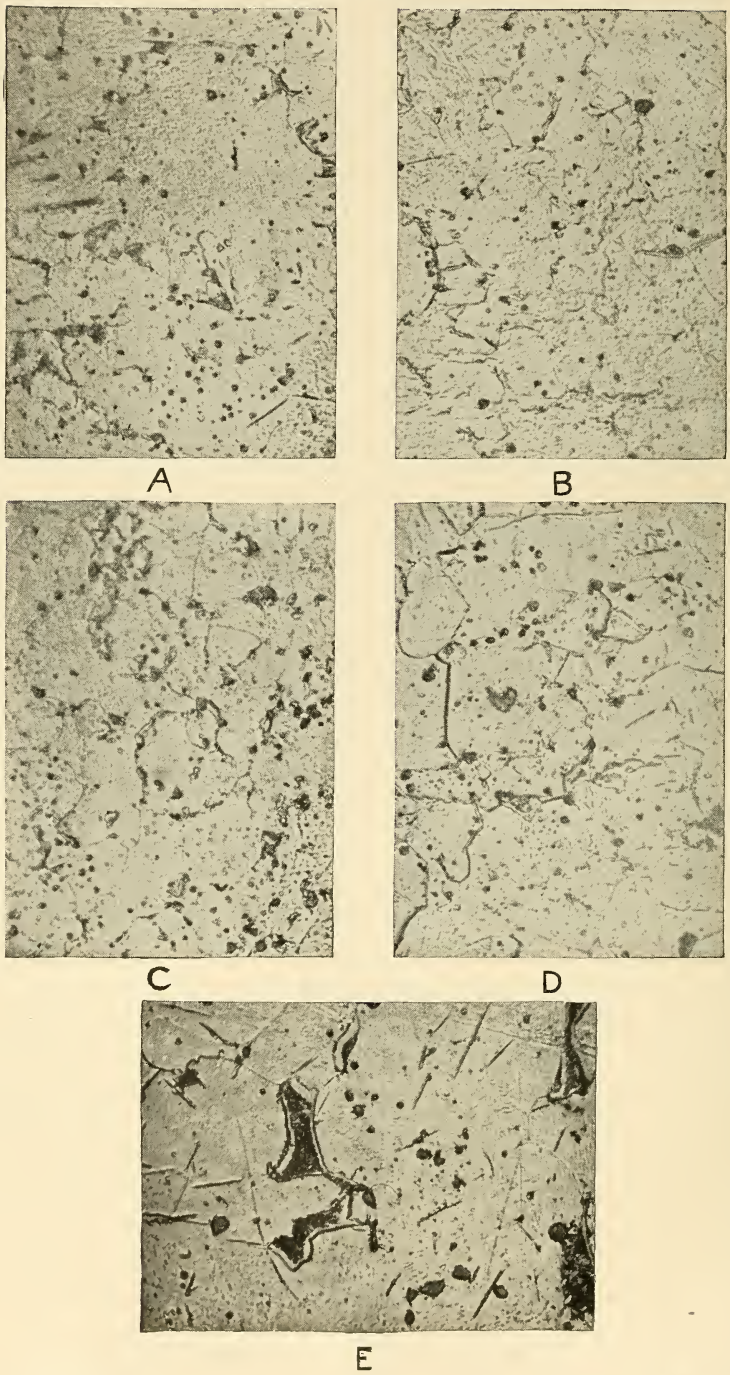


FIG. 23.—*Microstructure of arc-fused steel, type B, showing the effect of heat treatment.* × 500

The specimen B–2 (Table 6) was quenched in water from approximately 1000° C and reheated as shown below. *A*, arc-fused metal as deposited; *B*, a quenched specimen was reheated to 650° C; no plates have appeared after this treatment; *C*, a quenched specimen was reheated to 700° C; a few plates have appeared; *D*, a quenched specimen was reheated to 800° C; *E*, a quenched specimen was reheated to 925° C. Etching reagent, 2 per cent alcoholic solution of nitric acid

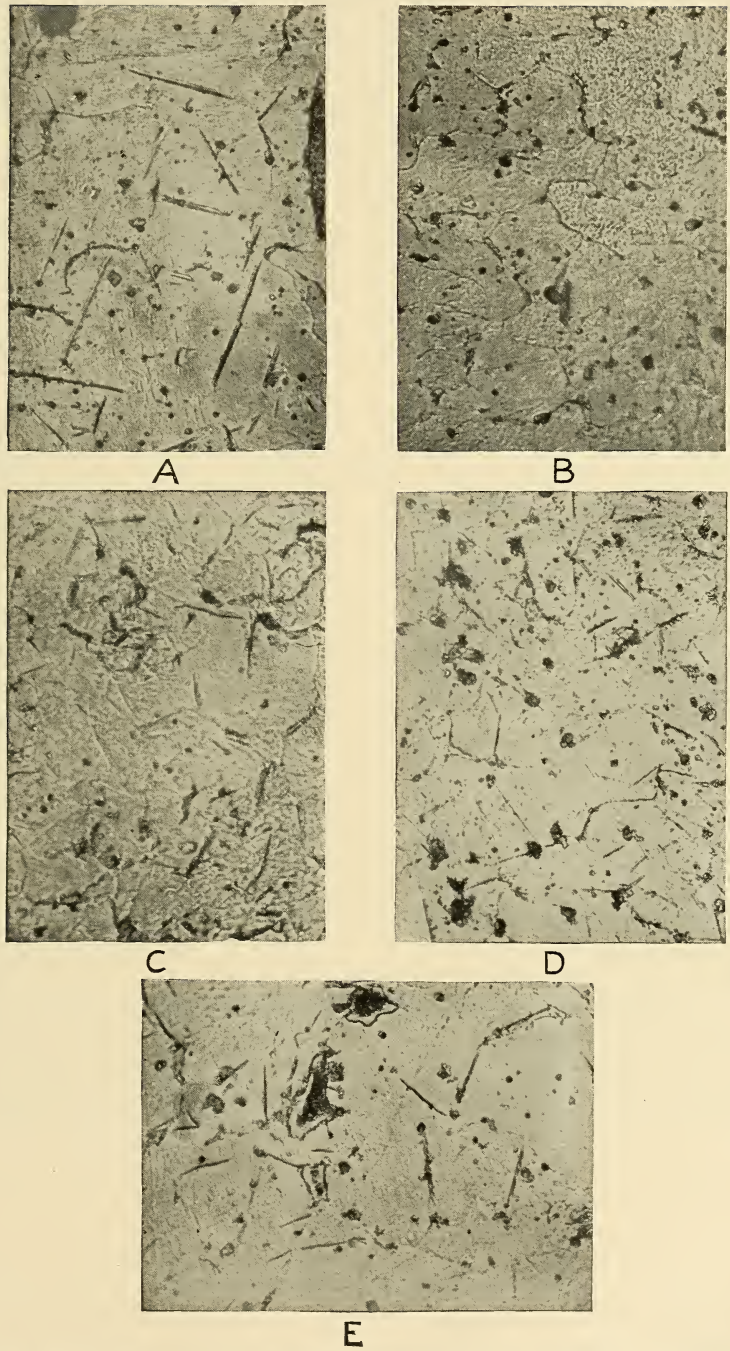


FIG. 24.—*Microstructure of arc-fused steel, type B, showing the effect of heat treatment.* × *500*

The specimen B–9 (Table 6) was quenched in water from approximately 1000° C and reheated as shown below. *A*, arc-fused metal as deposited; *B*, a quenched specimen was reheated to 650° C; no plates were formed by this treatment; *C*, a quenched specimen was reheated to 700° C; a few plates have appeared; *D*, a quenched specimen was reheated to 925° C. Etching reagent, 2 per cent alcoholic solution of nitric acid

Fig. 12*c* illustrates an interesting exception to the rule that the nitride plates are flat. In the metallic globule inclusion shown the plates have a very pronounced curve. The general appearance suggests that the "metallic globules" solidified under a condition of constraint, and that this condition still persists even after the six hours' heating at 1000° C which the specimen received.

Several of the specimens which were heated in vacuo were analyzed for nitrogen. The results are given in the table below.

TABLE 9.—Change in Nitrogen Content of Arc-Fused Metal upon Heating [a]

Specimen	Weight of sample	Hours of heating in vacuo at 1000° C	Average nitrogen content		Loss
			Before heating	After heating	
	Grams		Per cent	Per cent	Per cent
A-3	1.39	6	0.127	0.062	51
B-4	6.0	6	.124	.078	37
BD-5	1.62	6	.140	.059	57
B-5	1.16	6	.121	.054	55
AD-2	1.28	10½	.149	.043	71
B-2	1.76	10½	.152	.050	67
AD-6	2.23	10½	.134	.061	54

[a] The method used for the determination of the nitrogen gives only the *nitride* nitrogen; hence a possible explanation for the change in the nitrogen content is that it has been converted into another form than nitride and may not have been eliminated as the results apparently indicate.

The fact that the specimens lose nitrogen upon heating, although the amount remaining is still many times the nitrogen content of the metal before fusion, coupled with the fact that the "nitride plates" are larger and more conspicuous after heating than before, suggests very strongly that these plates are not simple nitride of iron. In some of the specimens heated in vacuo at 1000° C for the longer period many of the crystals contain the smaller or secondary lines (Fig. 26*a*), previously referred to (p. 33). This would indicate that these secondary lines represent a transition stage. In some of the crystals (Fig. 26*b*) the lines have assumed an appearance which suggests that they are a crystalline phenomenon somewhat similar to Neumann bands.

4. THERMAL ANALYSIS OF ARC-FUSED STEEL [7]

In order to throw further light on the nature of the plates (nitride) found in the metal after fusion in the arc, the thermal characteristics of the electrode material before and after fusion as revealed by heating and cooling curves were determined.

[7] Credit is due to Howard Scott, assistant physicist, for the work described in this section.

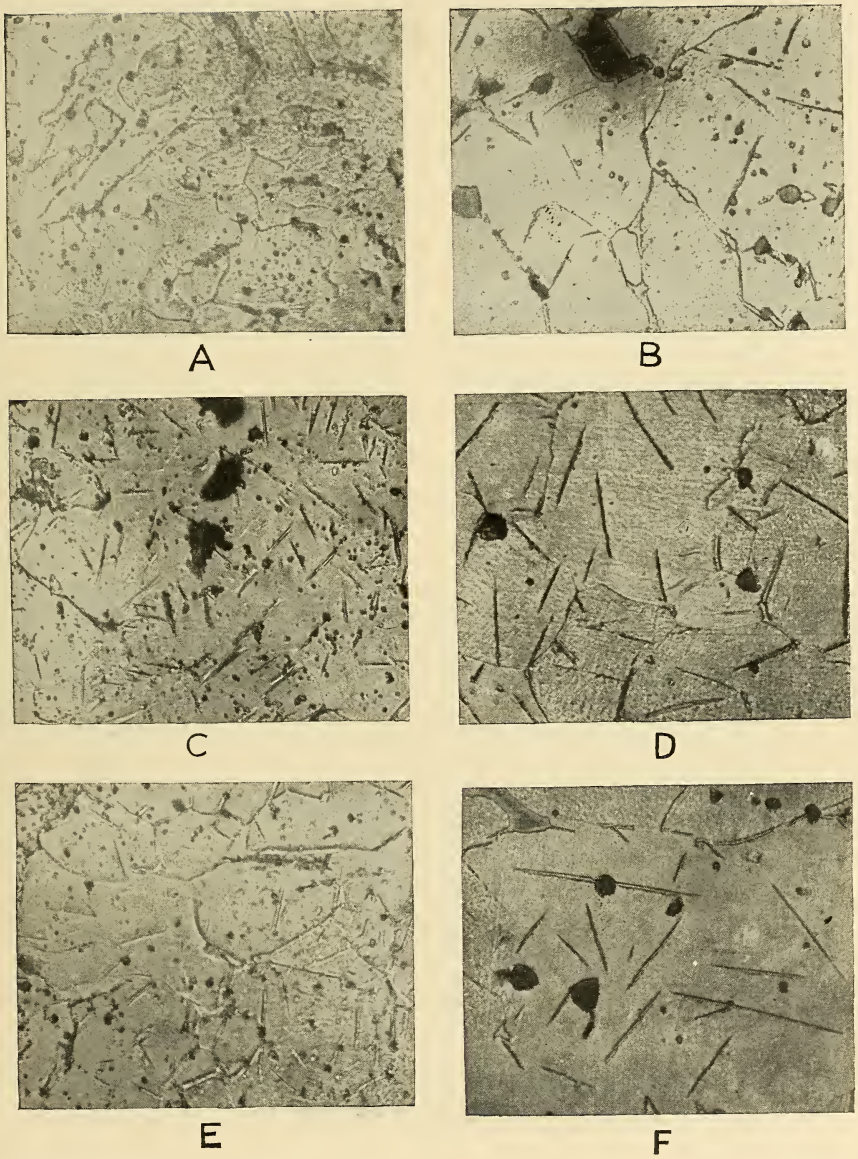


FIG. 25.—*Microstructure of arc-fused iron showing the effect of heating in vacuo at a high temperature.* × *500*

The specimens were heated continuously for 6 hours at 1000° C in vacuo. *A*, specimen AD–2, initial structure; *B*, same as *A*, after heating; *C*, specimen B–4, initial structure; *D*, same as *C* after heating; *E*, specimen A–10, initial structure; *F*, same as *E*, after heating. *B*, *D*, and *F* all show some cementite at grain boundaries which resulted from the "divorcing" of pearlite. Many of the plates appear to have been influenced in their position by an oxide globule. Etching reagent, 2 per cent alcoholic solution ol nitric acid

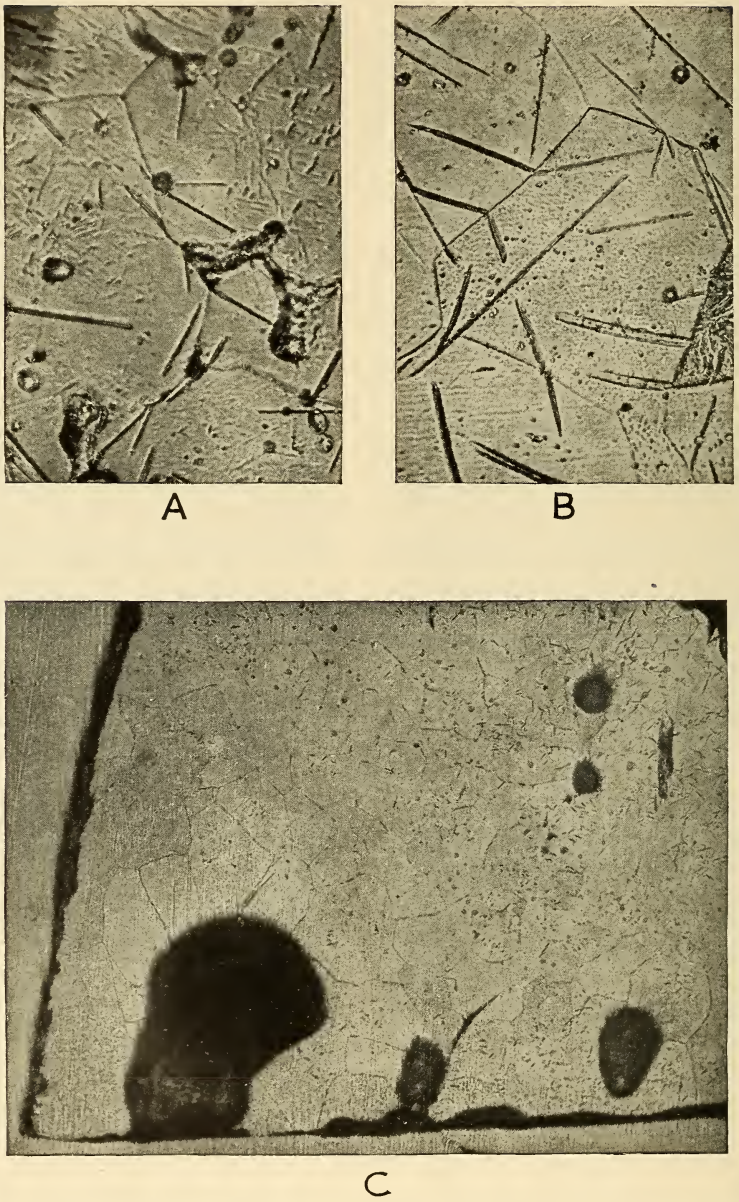


FIG. 26.—*Microstructure of arc-fused steel showing the effect of prolonged heating at high temperature*

A, specimen AD-2 (Table 6) was heated in vacuo for 10½ hours at 1000° C in stages of 6 and 4½ hours; two generations of "plates" have appeared after this treatment, × 500; *B*, specimen AD-6 (Table 6) heated as in *A* above; the plates which have persisted are relatively large and resemble Neumann bands in appearance, × 500; *C*, specimen AD-10 (Table 6) heated 6 hours in vacuo at 1000° C; the micrograph represents a corner of the specimen; the oxide and the "nitride plates" have been removed at the exposed corner, × 100

Samples of a three-sixteenths-inch electrode of type A and of the specimen, A–5, which resulted from the fusion were used as material (composition in Tables 3 and 6).

In Fig. 27 are given the curves obtained which show the characteristic behavior of the arc-fused metal upon heating. The commonly used inverse-rate method was employed in plotting the data; the details of manipulation and the precautions necessary for the thermal analysis have already been described.[8] In Table 10 are summarized the data shown graphically in Fig. 27.

TABLE 10.—The Thermal Characteristics of Arc-Fused Iron

UNFUSED ELECTRODE

Rate of heating and cooling	Ac_2 maximum	Ac_3				Time above A_3	Ar_3			Ar_2 maximum
		Beginning	Maximum	End	Maximum temperature		Beginning	Maximum	End	
°C sec.	°C	°C	°C	°C	°C	Minutes	°C	°C	°C	°C
[a] 0.16 / [a] .15	768	892	910	918	960	.....	896	893	879	766
.15	765	897	911	916	960	.....	895	891	879	766
ARC-FUSED METAL [b]										
0.14	764	.....	847	874	960	28	847	838	820	764
.13	764	.....	849	876	985	42	847	836	822	764
.13	764	.....	844	870	960	29	847	837	821	765
.13	766	.....	850	874	1035	256	848	835	816	764

[a] Heated at rate of 0.16° C per second, cooled at 0.15° C per second; for other specimens the rate of cooling equaled the rate of heating.

[b] The same specimen was heated four times in succession, as shown.

The principal change to be noted which has resulted from the arc fusion of the iron is in the A_3 transformation. This is now very similar to the corresponding change observed in a very mild steel (for example, approximately 0.15 per cent carbon). That the difference in the A_3 transformation of the arc-fused metal as compared with that of the original electrode is not due to an increase in the carbon content is evident from the lack of the sharp inflection of the A_1 transformation ("pearlite point"), which would, of necessity, be found in a low-carbon steel. No evidence of the A_1 change was observed for the arc-fused iron within the range of temperature, 150 to 950° C. The change in the character of the A_3 transformation is without doubt to be attributed to the influence of the increased nitrogen content of the iron.

[8] H. Scott and J. R. Freeman, B. S. Sci. Papers, No. 348.

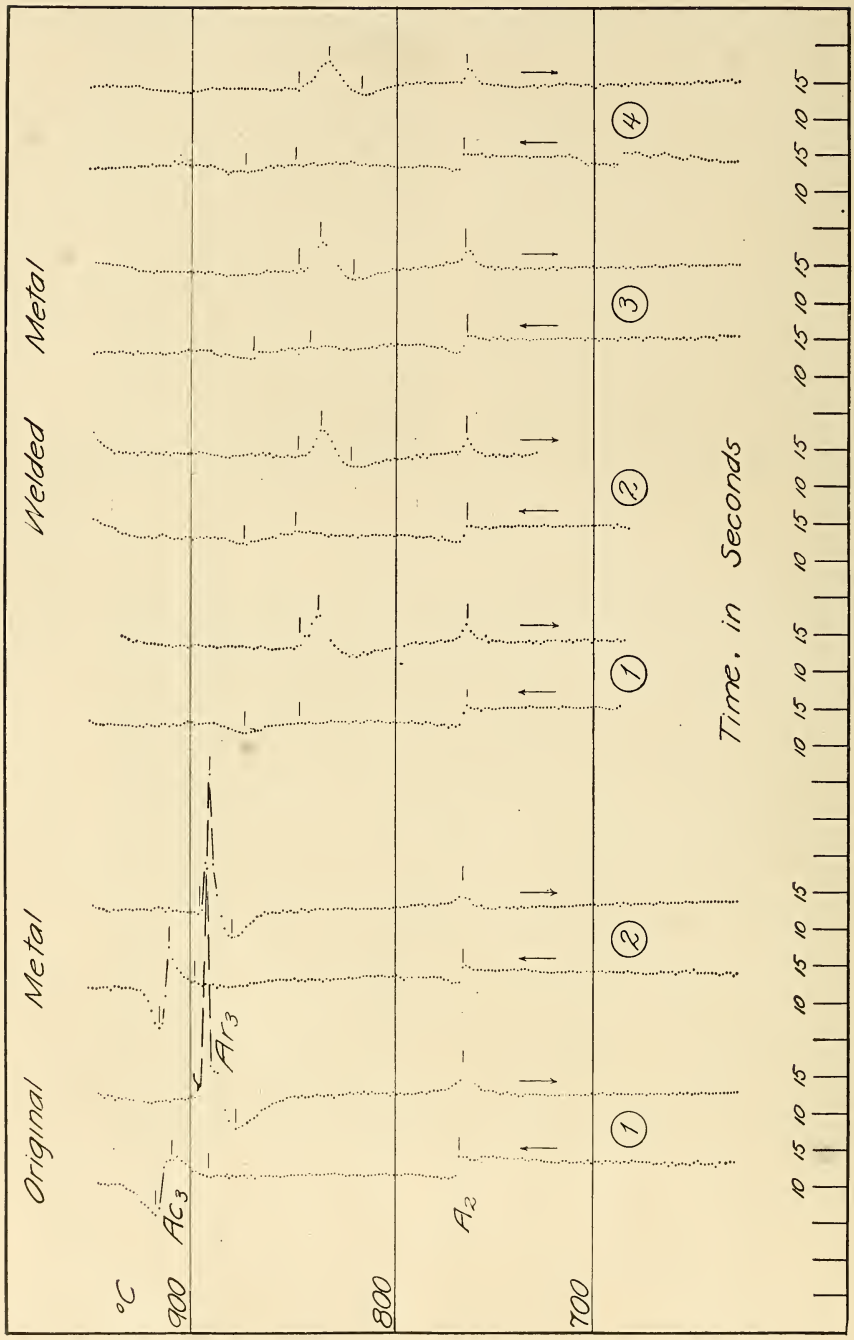
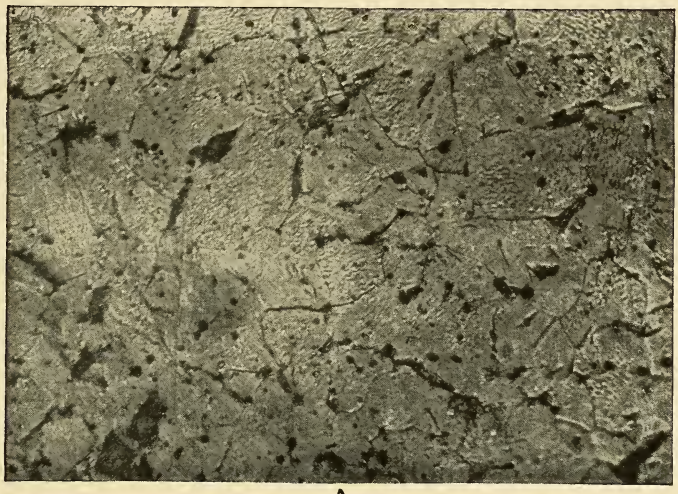


FIG. 27.—*Thermal characteristics of arc-fused steel*

The direction of arrow indicates whether the curve is a heating or a cooling curve. The numerals indicate the number of "runs" taken on the same specimen

The specimen was maintained above the temperature of the A_3 transformation for a total period (four heatings) of six hours, the



A

B

FIG. 28.—*Microstructure of the arc-fused metal used in thermal analysis.* × *500*

The specimen A–5 was heated four times as shown in Fig. 27. The total length of time above the temperature of the Ac_3 transformation was 6 hours. *A*, initial structure as fused; *B*, structure after heating. Etching reagent, 2 per cent alcoholic solution of nitric acid

maximum temperature being 1035° C. The transformation apparently is unaffected by the long-continued heating, thus confirming the results described in the preceding section. In

Fig. 28 are given micrographs to show the change of structure occurring in the specimen.

In discussing the properties of steel nitrogenized by melting it in nitrogen under pressure, Andrew [38] states that it was found possible to extract almost entirely the small quantities of nitrogen by heating a specimen at 1000° C in vacuo for periods of one to six hours. The metal used contained 0.16 per cent carbon and 0.3 per cent nitrogen. Thermal curves are given to show that there are no critical transformations in the material; the nitrogen suppresses them. They gradually reappear, however, as the nitrogen is removed by heating the material in vacuo at 1000° C. Several days' heating was required, however, to obtain an entirely degasified product, the carbon also being removed. A further statement is made that a steel of 0.6 per cent carbon content containing 0.25 per cent nitrogen can be brought back to the normal state of a pure steel only by several weeks' heating in vacuo.

The results of the thermal analysis add considerable confirmatory evidence to support the view that the plates existing in the arc-fused metal are due to the nitrogen rather than to carbon.

VIII. DISCUSSION OF RESULTS

In any consideration of electric-arc welding it should be constantly borne in mind that the weld metal is simply metal which has been melted and has then solidified in situ. The weld is essentially a casting, though the conditions for its production are very different from those ordinarily employed in the making of steel castings. The metal loses many of the properties it possesses when in the wrought form, and hence it is not to be expected that a fusion weld made by any process whatever will have all the properties that metal of the same composition would have when in the forged or rolled condition. A knowledge of the characteristic properties of the arc-fused iron is then of fundamental importance in the study of the electric-arc weld.

The peculiar conditions under which the fusion took place also render the metal of the weld quite different from similar metal melted and cast in the usual manner. It is seemingly impossible to fuse the metal without serious imperfections. The mechanical properties of the metal are dependent, therefore, to an astonishing degree upon the skill, care, and patience of the welding operator. The very low ductility shown by specimens when stressed in tension is the most striking feature observed in the mechanical

properties of the material as revealed by the tension test. As explained above, the measured elongation of the tension specimen does not truly indicate a property of the metal. Due to the unsoundness, already described in the discussion of the structure, the true properties of the metal are not revealed by the tension test to any extent. The test measures, largely for each particular specimen, the adhesion between the successively added layers, which value varies considerably in different specimens on account of the unsoundness caused by imperfect fusion, oxide, and other inclusions, tiny inclosed cavities, and similar undesirable features. The elongation measured for any particular specimen is due largely, if not entirely, to the increase of length due to the combined effect of the numerous tiny imperfections which exist throughout the sample.

That the metal is inherently ductile, however, is shown by the behavior upon bending as recorded in the microstructure of the bent specimen. The formation of slip bands within the ferrite grains to the extent which was observed is evidence of a high degree of ductility. It appears, however, that the grosser imperfections are sufficient to prevent any accurate measurement of the real mechanical properties of the metal from being made. The conclusion appears to be warranted, therefore, that the changes of composition which the fusion entails, together with the unusual features of microstructure which accompany the composition change, are of minor importance in determining the strength, durability, and other properties of the arc weld.

The view that the characteristic features observed in the structure of the arc-fused iron are due to the increased nitrogen content is supported by several different lines of evidence. These include the likeness of the structure of the material to that of pure iron which has been "nitrogenized," the similarity in the behavior of both arc-fused and nitrogenized iron upon heating, the evidence shown by thermal analysis of the arc-fused metal, together with the fact that, as shown by chemical analysis, the nitrogen content increases during fusion while the other elements, aside from oxygen, decrease in amount. The characteristic form in which oxide occurs in iron, together with its behavior upon heating, renders very improbable the assumption that the oxide is responsible for the plates observed in the material.

In arc-fusion welds in general, the mass of weld metal is in intimate contact with the parts which are being welded, so that it is claimed by many that because of the diffusion and inter-

mingling of the metal under repair with that of the weld the properties of the latter are considerably improved. The comparison shown in the table below somewhat supports this claim. The nearest comparison found available with this Bureau's specimens are some of those of the welds designated as the "Wirt-Jones" series reported by H. M. Hobart [1]. These welds were of the 45° double-V type made in one-half-inch ship plate; the specimens for test were of uniform cross section 1 by one-half inch, the projecting metal at the joint having been planed off even with the surface of the plates and the test bars were so taken that the weld extended transversely across the specimen near the center of its length. The electrodes used were similar to those designated as type B in this Bureau's investigation.

TABLE 11.—Comparison of Mechanical Properties of Welds with Results of Tests of Arc-Fused Metal Prepared under Similar Conditions

Bureau of Standards				Wirt-Jones			
Diameters of electrodes	Direct current	Ultimate tensile strength	Elongation in 2 inches	Diameter of electrode [a]	Direct current	Ultimate tensile strength	Elongation in 2 inches
	Amp.	Lbs./in.²	Per cent		Amp.	Lbs./in.²	Per cent
1/8 inch [a]	110	52 650	7.5	1/8 inch	110	45 800	8.0
1/8 inch [b]	110	49 050	9.0	1/8 inch	115	58 200	14.0
1/8 inch [b]	110	44 400	6.5	1/8 inch	115	59 400	13.5
	.....	.....	.....	1/8 inch	120	53 700	7.0
	.....	.....	.....	1/8 inch	120	57 600	8.5
Average	.....	48 700	7.7	Average	.....	54 940	10.2
5/32 inch [a]	145	46 450	5.0	11/64 inch	150	60 900	8.0
5/32 inch [b]	145	48 130	8.0	5/32 inch	155	62 600	11.5
5/32 inch [b]	145	41 750	.....	.....	.....	.....	.....
Average	.....	45 440	6.3	Average	.....	61 750	9.8
5/32 inch [a]	185	49 600	7.5	11/64 inch	175	59 800	9.0
5/32 inch [b]	185	49 086	12.5	.....	.....	.....	.....
5/32 inch [b]	185	47 100	11.0	.....	.....	.....	.....
Average	.....	48 595	10.3	.....	.....	.....	.....

[a] Electrodes were used in bare condition. [b] Electrodes were coated as previously described.

Since the specimens used in work described in the foregoing sections were prepared in a manner quite different from the usual practice of arc welding, no definite recommendations applicable to the latter can be made. It appears, however, from the results obtained that the two types of electrodes used—that is, "pure" iron and low-carbon steel—should give very similar results in practical welding. This is due to the changes which

occur during the melting, so that the resulting fusions are essentially of the same composition. The use of a slight coating on the electrodes does not appear to be of any material advantage so far as the properties of the resulting fused metal are concerned. Since the program of work as carried out did not include the use of any of the covered electrodes which are highly recommended by many for use in arc welding, particularly for "overhead work," no data are available as to the effect of such coatings upon the properties of the metal resulting from fusion. Although all of the specimens used in the examinations were made by the use of direct current, it appears from the results obtained with a considerable number of welds representing the use of both kinds of current, submitted for the preliminary examinations, that the properties of the fused metal are independent of the kind of current and are influenced primarily by the heat of fusion. Any difference in results obtained by welding with alternating current as compared with those obtained with direct current apparently depends upon the relative ease of manipulation during welding rather than upon any intrinsic effect of the current upon properties of the metal.

IX. SUMMARY

1. A fusion weld is fundamentally different from all other types in that the metal of the weld is essentially a casting. The arc-fusion weld has characteristics quite different from other fusion welds. A preliminary study of a considerable number of specimens welded under different conditions confirmed this general opinion concerning arc welds. A knowledge of the properties of the arc-fused metal is fundamental in any study of electric-arc welding.

2. Blocks of arc-fused metal of size large enough to permit a tension specimen (0.505 inch diameter, 2-inch gage length) to be taken from each were made under different conditions of fusion. Two types of electrodes, a "pure" iron and a mild steel, were used in the bare condition and also after receiving a slight coating. With these were included a set of similar specimens prepared outside of this Bureau by expert welding operators.

3. During the fusion the composition of the metal of both types of electrodes is changed considerably by the burning-out of the carbon and other elements, and the two become very much alike in composition. A very considerable increase in the nitrogen content occurs at the same time.

4. The mechanical properties of the arc-fused metal as measured by the tension test are essentially those of an inferior casting. The most striking feature is the low ductility of the metal.

5. All of the specimens showed evidence of unsoundness in their structure, tiny inclosed cavities, oxide inclusions, lack of intimate union, etc. These features of unsoundness are, seemingly, a necessary consequence of the method of fusion as now practiced. They determine almost entirely the mechanical properties of the arc-fused metal. The observed elongation of the specimen under tension is due to the combined action of the numerous unsound spots rather than to the ductility of the metal. That the metal is inherently ductile, however, is shown by the changes in the microstructure produced by cold bending. By taking extreme precautions during the fusion, a great deal of the unsoundness may be avoided and the mechanical properties of the metal may be considerably improved. However, the specimens as described are more representative of actual present practice in welding.

6. A very characteristic feature of the microstructure of the arc-fused metal is the presence of numerous plates within the ferrite crystals, arranged usually along crystallographic planes. These persist in the metal after prolonged heating; for example, ten hours at 1000° C in vacuo does not remove them. The various lines of evidence available indicate that they are related to the nitrogen content of the metal, which is increased during the fusion.

7. Upon heating the metal above the temperature of the Ac_3 transformation, the nitride enters into solid solution in the ferrite and is retained so by quenching. Upon heating this quenched metal, the plates reappear and begin to show at a temperature of approximately 700° C. The effect of nitrogen upon the Ar_3 transformation is very similar to that of an equal amount of carbon. However, there is no evidence of a transformation corresponding to the A_1 or the pearlite change due to the nitrogen in the steel.

8. The microscopic examination indicates that there is but little, if any, relation between these nitride plates and the path of rupture produced by tension. The effect of grosser imperfections of the metal is so much greater than any possible effect of the nitride plates in determining the mechanical properties that the conclusion appears to be warranted that this feature of the structure is a matter of relatively minor importance in ordinary arc welds.

9. Judged from the results obtained, neither type of electrode appears to have a marked advantage over the other. The use of a slight protective coating on the electrodes does not appear to affect materially in any way the mechanical properties of the arc-fused metal.

10. The specimens were prepared in a manner quite different from that used ordinarily in electric-arc welding, and the results do not justify any specific recommendations concerning methods of practice in welding.

Credit is due to H. L. Whittemore and R. W. Woodward for aid in the necessary mechanical testing, and to F. H. Tucker for the general chemical analyses made.

WASHINGTON, June 7, 1920.

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