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First Partial Report

of

Research of the Weldability of Iron Alloys

by

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NAVAL RESEARCH LABORATORY

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NAVY DEPARTMENT

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First Partial Report

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Research of the Weldability of Iron Alloys.

NAVAL RESEARCH LABORATORY
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ABSTRACT

This study is concerned with the effects of the arc-welding operation on the properties of the base metal. In particular, the study concerns the physical changes producedin the base-metal, such as grain-growth or refinement, hardening, and embrittlement.

The present partial report deals with results to date, including a method of reproducing conditions in the heat disturbed region of a weld by an artificial quenching operation on a special specimen.

AUTHORIZATION

1. This investigation was authorized by Bureau of Engineering letter JJ46-1/L5(4-2-Ds) of 4 April 1935.

STATEMENT OF PROBLEM

2. The problem concerns an investigation of the hardening effects and lack of toughness observed with iron alloys when they are quenched, or rapidly cooled from the high temperatures imposed on them by the fused weld metal.

3. In more detail, the problem is divided into the following parts:

(a) To determine the maximum hardness of the metal of the transition zone, next to the weld bead as a function of the carbon and alloy content of a series of iron alloys in the "as rolled" condition.

(b) To determine the microstructure and grain size of the transition zone for the same series of iron alloys in (a).

(c) To determine a heat treatment for each alloy in the series to duplicate (a) and (b) in order to synthesize metal of the transition zone in a weld.

(d) To determine the ductility and toughness (impact resistance) of the iron alloys when treated as in (c).

(e) To determine the effect of preheating on the maximum hardness (a) of the transition zone when those iron alloys of the series having higher hardening propensities are welded.

(f) To determine for a series of iron alloys in the "as cast" condition the factors under (a), (b), (c), (d) and (e).

4. In order to produce welds for the determination of maximum hardness encountered in welding of the iron alloys, the depositing of a single bead on flat plates of the alloys is contemplated for the program as the simplest and most easily reproducible condition. In an actual weld, the transition zone in the parent metal would be heated and reheated by successive weld beads and would be difficult to reproduce.

5. The determination of ductility and toughness of material in the transition zone having maximum hardness, grain size and microstructure, as in (a), (b), (e), would be impractical with an actual weld due to the limited size of the transition zone. It is therefore necessary to carry out (d) by first preparing as in (c) samples of sufficient size with which tests for ductility and toughness can be made.

KNOWN FACTS BEARING ON THE PROBLEM

6. The higher strength steels owe their high strength to their higher carbon, higher alloy or higher contents of both carbon and alloy.

The plain carbon steels are considered to produce an unsafe structure in the "as welded" condition when the carbon content is above 0.35%. No definite limits as to weldability have been defined for the alloy contents except for the general rule that the higher the alloy content the lower the carbon must be to prevent excessive hardening in the transition zone.

7. The higher strength steels of carbon contents above 0.35% and high alloy contents are being successfully welded in the preheated condition and in many cases heat treatment after welding is a necessity for these steels.

8. The repair of castings by welding has also been successfully pursued to give machineable, crackless welds where preheating before welding and heat treatment after welding has been resorted to.

THEORETICAL CONSIDERATIONS

9. The hardness of the hypoeutectic iron alloys, hardenable by precipitation of carbide and decomposition of the austenite formed at high temperatures is dependent upon the temperature to which they are heated and the rate at which they are cooled or quenched from this temperature. The rate at which they are heated to the quenching temperature and the time they remain at temperature has a pronounced effect on the grain size but only a slight effect on the hardness.

10. In the transition zone of a weld, the parent metal has been quenched from temperatures ranging from 1450°C down to 700°C. We find, therefore, that the portion of the transition zone immediately adjacent to the weld, where the maximum temperatures of 1450°C to 1400°C have existed, is the part of the zone with the largest grain size and maximum hardness. In the portion of the transition zone adjacent to the undisturbed parent metal where the temperature may have risen to 700°C - 900°C, there is found a region where the grain size may be smaller than that of the original metal due to recrystallization in this region. Between the regions of maximum and minimum temperatures we find grain size and hardness varying progressively.

11. For an arc weld, the width of the transition zone is much smaller than is the case for an oxy-acetylene weld and for a single bead arc weld, such as is contemplated for the present program, the transition zone may extend for only .05 to .10 inches on either size of the weld. The variation in hardness progressively across this narrow zone is obtainable with a suitable hardness testing machine, but physical tests to determine ductility and toughness are not possible. However, the microstructure and grain size of the transition zone are associated with a definite hardness, all of which can be determined with a single bead weld.

12. With the information as to hardness, grain size and microstructure, if a heat treatment is given samples of the parent metal such as to duplicate these three physical properties, then the mechanical properties of ductility and toughness of the synthetically produced material should be the same as the same region in the welded material. Actually,

the entire range of temperatures from 1450°C to 700°C will not be investigated and the problem is simplified by considering the range from 1400°C to 800°C in steps of 100°C.

METHODS AND MATERIALS

13. A series of steels was assembled at the Laboratory from industrial sources. The steels are in the form of rolled plate 1/2-inch thick, in general, and 6 inches wide. The approximate analyses of these materials are given in the following schedule.

Stock List of Materials

Item No.	C	Mn	Si	Ni	Cu	Mo	V	Cr	
A	.17	-	-	-	-	-	-	-	Unknown history.
1	.15	.50	.15-.30	-	-	-	-	-	Plain carbon-killed heat
2	.25	.50	.15-.30	-	-	-	-	-	
3	.35	.50	.15-.30	-	-	-	-	-	
5	.15	.50	less than-.06		-	-	-	-	Rimmed heat-carbon
6	.25	.50	"		-	-	-	-	
9	.25	.40	.15-.30	-	-	-	-	-	Manganese steels
10	.25	.70	.15-.30	-	-	-	-	-	
11	.28	1.06	.25	-	-	-	-	-	
13	.25	.50	.02 max.-		-	-	-	-	Silicon series
14	.25	.50	.08	-	-	-	-	-	
15	.25	.50	.20	-	-	-	-	-	
17	.25	.50	-	-	-	.20	-	-	Molybdenum series
18	.25	.50	-	-	-	.50	-	-	
19	.25	.50	-	-	-	.80	-	-	
20	.25	.50	.02	-	-	-	-	-	Boiler steels
21	.25	.50	.25	-	-	-	-	-	
22	.15	1.30	.25	-	-	-	.10	-	
23	.15	.44	.20	-	.75	.17	-	-	
24	.28	.56	.27	3.57	-	-	-	-	
27	.06	.35	.002	1.95	1.02	-	-	-	Yoloy steels
28	.21	.70	.27	1.97	.92	-	-	-	
29	.045	.17	-	2.08	-	-	-	-	2% Nickel iron
30	.08	.70	-	.75	1.40	-	-	-	R.D.S. (Republic Double Strength)
31	.23	.75	-	.75	1.30	-	-	-	

Stock List of Materials - Continued.

Item No.	C	Mn	Si	Ni	Cu	Mo	V	Cr	
32	max. .14	1- 1.25	.60- .80	-	-	-	-	.40- .60	Cromansil
33	max. .10	-	-	-	-	.40-.60	-	4-6	Low Chrome
34	.07	-	-	Cb=.55	-	.50	-	5.50	
35	.22	-	-	2.5	-	-	-	-	
B	.26	.64	.20	-	-	-	-	-	

14. The source of the steels is given below as:

Item #1, 2, 3, 5, 6, 9, 10, 13, 14, 15, 20, 21, 22 - Lukens Steel Company

Item #17, 18, 19, 23 - Climax Molybdenum Company
Item #11, 29, 30, 21 - Republic Steel Company
Item #24 - Illinois Steel Company

Item #31, 32, 33 - Union Carbide and Carbon Company

Item #27, 28 - Youngstown Sheet and Tube Company

Item #A - Hot rolled mild steel from Naval Research Laboratory Machine Shop Stock.

Item #B - 1-1/2" thick hull plate, grade M, from Washington Navy Yard.

15. The steels which have been ordered but have not been received are:

Item	Analysis
4	Same as 1, 2, 3, except for 0.45% C. Ordered from Lukens Steel Company.
7	Same as 5, 6, except for 0.35% C. Ordered from Lukens Steel Company.
36	Same as 35, except for 1-7/8" thickness. Ordered from Lukens Steel Company.

16. A 100-pound lot of heavy coated 3/16" U.N.A. (grade 2100) welding rod has been purchased for use in weld tests of the above materials. These electrodes were discovered to be not on the Navy Department's approval list, therefore another order has been sent through for 100 pounds of Airco #78 heavy coated rod, the same size as those already used for the weld tests. The Airco #78 rods are on the Navy's approved list and meet the A.S.M.E. specification for Class 1 welds with tensile strength 60,000 to 75,000 lbs. per square inch and 22-30% elongation in 2 inches.

17. A Vickers type, pyramidal, hardness testing machine has been ordered, but has not been received. It is so essential to have a hardness testing machine of this type that exact results on the correlation of hardness in the weld zone with hardness of quenched samples must be held in abeyance until the instrument purchased can be put to use.

18. A welding machine has been constructed to produce welds by a semi-automatic arrangement. The machine is shown in Plate 1. An investigation of the degree of reproducibility of the hardness in the heat disturbed zone was made on three identical plates of item A, 3" wide, 5-1/2" long, and approximately 1/2" thick. The current, voltage and welding speed were kept the same for all plates. After depositing a single bead on each of the plates, a half-inch section was cut from each plate, transverse to the weld. The sections were polished and macro-etched to define the weld and the heat disturbed region and Rockwell B hardness measurements were made on these regions. The results are given below and a photograph of the three plates and etched sections are shown in Plate 3.

19. Welds have been made with the semi-automatic welder on items 2, 6, 11, 13, 15, 17, 18, 19, 20, 21, 22, 24, 27, 28, 29, 30, 31 and 1/2" sections cut out and polished for a progressive hardness survey across the weld into the unaffected plate. It is expected that the hardness testing machine will be available for use in the near future in order to complete the study of these welded plates. The remaining steels on the above list will be cut into 3" x 6" x 1/2" plates as expeditiously as possible and treated in the same manner as described for those already welded.

Weld Quench Tests

20. Before any of the steels ordered from the industry became available, item A was obtained from the Machine Shop stock at the Laboratory and subjected to welding and weld-quench tests for preliminary information as to hardness, grain size, cooling rate, etc. For the weld-quench studies, a number of samples 1/2" x 1/2" x 3/4" were cut from the item A plate and each sample **subjected to test was identified** with a stamped code on each of the 1/2" x 1/2" cross section ends. These samples were heated in triplicate at temperatures from 1400°C to 800°C in steps of 100°C for time intervals ranging from 5 to 30 minutes, the heating being accomplished in a carbon resistance furnace. The samples, after removal from the furnace, were subjected to three different cooling rates, e.g. in water, oil and air, and were then cut in half through the 3/4" length by means of a friction wheel. One half of the sample was used for hardness determinations on the Rockwell hardness testing machine, the other half of the sample was used for a polished and etched micro-section to determine the structural constituents and grain size. The results for this preliminary study are given below.

21. As a result of the preliminary study of weld-quench hardness for small samples of item A, it was found necessary to repeat the high temperature treatment on this item by holding the samples for intervals of time, shorter than five minutes. Samples 1/2" x 1/2" x 3/4" of the following items A, 2, 6, 11, 13, 15, 17, 18, 19, 20, 21, 22, 24, 27, 28, 30 and 31 have been prepared by heating at 1400°C, 1300°C and 1200°C for

1 to 5 minutes and quenching in air. These have been sectioned for hardness tests and micro-sections and are being prepared for these tests. It will be possible to obtain more exact data on these samples as soon as the pyramidal hardness testing machine is available for use. However, measurements have been made with the Rockwell machine using the 1/16" ball or diamond cone for R_B and R_D readings for all the welds above and for some of the quenched samples.

DATA OBTAINED

22. Table 1 gives a number of hardness values obtained in the weld-quench test samples for item A. The hardness values were obtained with the Rockwell machine and have been converted to Brinell numbers for easier comparison.

23. The samples showed considerable variation in hardness from the outer edges of the cross-section to the center. The center was usually of maximum hardness due probably entirely to decarburization. The samples therefore had to be searched by a series of hardness tests and the maximum hardness found has been reported in Table 1.

24. The microstructures of the quenched samples referred to in Table 1 are shown on Plates 3, 4, 5, 6, 7, 8 and 9, with accompanying identification of the quenching condition. The microstructures of only one heat treatment, that at 1400°C, are shown because the minimum time at temperature was five minutes, which produced a greater coarsening of the grain size than is the case for material next to the weld. The grain size of these quenched samples may be compared with the zone of largest grain size next to the weld for two speeds of welding, as shown in Plates 10 and 11, and it can readily be seen that heating a 1/2" x 1/2" x 3/4" sample at 1400°C for five minutes has a much greater effect on grain size of item A than the welding arc heat has on the corresponding high temperature zone of the weld. The second series of quenching tests on samples held at temperatures of 1400, 1300, 1200°C for 1 to five minutes is reported partially in Table 2. For these samples, the decarburization was confined to a thin skin of the sample surface but there was still considerable hardness variation on the 1 to 3-minute samples, and accordingly the hardness values reported are those for the center of the sample only, rather than the maximum value.

25. In Table 2 are also given the results of a survey of the hardness of the welds prepared on the semi-automatic welder using 190 amperes, 26 volts and a speed of 9 inches per minute. The survey was made as best as possible with the R_D or R_B scale of the Rockwell tester. It must be understood that the values for the transition zone hardness, as reported in Table 2, are crude and represent an under-estimate of the true maximum as would be reported by a Vickers-type hardness machine. The values in Table 2 have been converted to Brinell and the hardness of the original plate included for comparison purposes.

26. The rest of the samples of series 2 have not been examined as yet and it will be noted that of the quenched samples only those treated at 1400°C for 4 minutes have been reported. It was therefore of interest to determine, on a low hardening grade item A and on a high hardening grade item 24, the hardness and microstructure when held at 1400°C for 1, 2 and 3 minutes.

The results for these two grades of steel are shown below in Table 3 in terms of Brinell values converted from Rockwell readings. The corresponding micrographs are shown in Plates 12, 13, 15 and 15 for item A and Plates 18, 19 and 20 for item 24, while Plates 11 and 17 show respectively the coarse grain area of the weld transition zone.

Weld Reproducibility Data

27. In order to test the semi-automatic welder, three plates of item A were prepared for weld tests. The plates were 3" x 5-1/2" x 1/2" and were welded under the same conditions with 190 amperes, 26 volts at a speed of 9 inches a minute, which is equivalent to roughly 33,000 Joules per inch. A 3/16" mild steel, U.N.A., 2100 grade of heavy coated rod was used in each case. The plates were clamped to the welding table shown in Plate 1 and the welder manipulated the feeding arrangement which moved the rod over the plate at a pre-set speed of 9 inches a minute.

28. After the welds were completed and the plates cold, they were sectioned as shown in Plate 2. The 1/2" section was polished, etched and the hardness of the transition zones checked with a Rockwell B penetrator. In each case the value was 89 and Plate 2 shows the etched sections to be practically identical.

CONCLUSIONS AND RECOMMENDATIONS

(a) Facts Established

29. It has been shown that it will be possible to duplicate exactly the maximum hardness of the weld-transition zone when samples of the plates are quenched from 1400°C. The indications so far are that the 1/2" x 1/2" x 3/4" samples used do not reach the maximum hardness of the transition zone of the welds in Table 2 when quenched in air; but Table 1 shows that by choosing a more rapid quench the hardness of the samples can be made to exceed that of the zone.

30. It has been shown by means of photomicrographs that the rate of grain growth at 1400°C, at least for one low hardening and one high hardening steel, is extremely rapid, such that before the sample of the size used can come up to furnace temperature (see Table 3) its grain size has already exceeded the largest grains in the transition zone. These data establish the fact that a short-time heat treatment at 1400°C of the order of 1 minute or less will be necessary in order to prevent excessive grain growth.

(b) Opinions and Recommendations

31. It has already been stated that it would be desirable to split the problem of weld-quench tests into two separate parts, with the problem of proper time-mass relationships for the duplication of grain size taking precedence over the problem of quenching rates to establish identical hardness. The most desirable direction in which to work would be to use the same 1/2" x 1/2" x 3/4" samples rather than still smaller pieces and to increase the rate of heating by conducting of heat from a large block of steel held in the furnace. It is intended to use a steel block with a suitable drilled hole to hold the samples, in which they will be held for short intervals of time ranging up to 2 minutes. If this method does not provide

the desired result in duplicating the grain size, it will be necessary to go to a sample size with cross-section of less than 1/2" x 1/2". The quenching rate of a smaller sample will necessarily have to be different from a larger sample in order to attain the same hardness. It is therefore seen to be the best procedure to settle the question of grain size first.

32. It is the opinion also that the maximum hardness of the transition zone of the welds reported in Table 2 is less than will actually be the case when it is possible to use the pyramidal hardness tester now being purchased. In comparison with the original plate hardness, the hardness of some of the welds in Table 2 (22, 24, 29, 31) are seen to be already so extreme as to be entirely out of line with conditions for manual welding. It is therefore to be recommended that a slower speed of welding of about 6 inches a minute be employed, giving approximately 50,000 Joules per inch instead of 33,000 as previously used. The 6-inch a minute speed will give a larger grain size in the zone and will be between the maximum shown for the 3-1/2" a minute weld, Plate 10), and a 9-inch a minute weld, Plate 11; it will be larger than the latter and therefore less difficult to duplicate in the weld-quench tests.

33. A comparison of the quenching tests shown in Table 2 with the welds is especially of interest for items 17, 18, 19 for the samples held for 4 minutes at 1400°C show identical core hardness, while the weld zone hardness increases with increasing molybdenum. It is more reassuring to note that item 24 has the maximum hardness of all items tested both in the weld-quench tests and the weld zone.

SUMMARY AND DISCUSSION

34. Results of the weld-quench tests have been presented in Tables 1 and 2 with corresponding micrographs of two of the plate materials included in the tests. Table 1 indicates that a quenching rate intermediate between air and oil cooling may have duplicated the maximum hardness of the welds reported in Table 2, but the lack of a suitable hardness tester to obtain true maximum ha[illegible] of the weld zone tempers the certainty of this conclusion.

35. [illegible] he comparison of Tables 1, 2 and 3, we find the core hardness of samples AB1, 2, 3, 4 of Table 3 to be somewhat less than the maximum [illegible]ess of samples A1, 2, 3, 4, 5 of Table 1; the latter appear to be constant while the former show a progressive increase. The indications are that the 4-minute samples of Table 3 either have not reached equilibrium with the furnace or the core is quenched at a lower rate than the surrounding mass. A difference in behavior between item A and 24 is shown in Table 3, where the core hardness of 24 apparently has not reached its maximum after 4 minutes at 1400°C. It is believed that the use of a steel block for increasing the conduction of heat to the samples, or the use of samples with smaller cross-section or both together, will clear up this difficulty as well as solving the problem of time at temperature to produce the desired grain size.

36. The problem of obtaining reproducible welds has been solved by the construction and use of a semi-automatic welder and the degree of reproducibility has been indicated. It has also been shown that a desirable speed of welding of the plates with the semi-automatic welder would be between 9 and 4 inches a minute, giving an energy input of about 50,000 Joules per inch,

which is equivalent to a speed of 6 inches a minute. The latter speed may still be higher than would be the case in practice for some of the higher hardening alloys, but the extreme hardnesses shown in Table 2 will be decreased to a certain extent.

37. The difficulties involved in the interpretation of the thermal history of the transition zone of a weld have been indicated in the theoretical discussion.

38. An extensive bibliography has been accumulated relating to the activities in research on welding reported in journals of the United States, Great Britain, France and Germany. This bibliography will be presented at a future time, since the literature is still being traced to determine studies of the heat effects of welding completed in the past. The current literature is also being followed for material pertinent to the problem. One of the most important articles found in the current French literature is given in the appendix.

TABLE 1.

The stamped identification marks on the samples followed the following code: the first letter is the item (A in this case), the second letter gives the quenching medium. A = air, W = water, O = oil.

Sample No.	Quenching Temperature	Time at Temperature (Minutes)	Maximum Brinell Hardness
AA1	1400°C	5	183
AA2	"	10	197
AA3	"	15	183
AA4	"	20	192
AA5	"	25	197
AW7	"	5	449
AW8	"	10	449
AW9	"	15	449
AW10	"	20	436
AO13	"	5	360
AO14	"	10	360
AO15	"	15	372
AO16	"	20	330
AA19	1300°C	5	143
AA20	"	10	143
AA21	"	15	149
AA22	"	20	149
AA31	1200°C	5	128
AA32	"	10	126
AA33	"	15	134
AA34	"	20	128
AA43	1100°C	5	116
AA44	"	10	116
AA45	"	15	121
AA52	1000°C	5	116
AA53	"	10	114
AA54	"	15	116
AA61	900°C	5	123
AA62	"	10	128
AA63	"	15	128
AA70	800°C	5	115
AA71	"	10	118
AA72	"	15	115

Original hot rolled bar of item A showed a hardness of 110 Brinell.

TABLE 2.

(Brinell hardness converted from R_D or R_B values)

Item No.	Core hardness of sample, 4 min. at 1400°C. Air quenched.	Maximum hardness in weld transition zone for single bead. 190 amps., 26 volts, 9 inches per minute.	Original Plate Hardness
A	149	174	110
2	179	187	121
6	167	248	137
29	134	159	115
13	156	277	134
15	163	235	146
17	217	248	149
18	217	293	156
19	217	331	174
20	159	241	118
21	192	248	137
22	229	429	192
24	293	534	201
27	163	197	128
28	241	477	179
11	-	364	183
30	207	269	159
31	223	364	207

TABLE 3.

Hardness Values on 1400°C, Air Quench Samples
(Brinell hardness converted from Rockwell)

Item	Sample No.	Time in Furnace at 1400°C (Minutes)	Air Quench Sample - Core Hardness	Microstructure for Coarsest Grain Found in Cross Section
A	AB1	1	123	See Plate 13
A	AB2	2	131	" " 14
A	AB3	3	149	" " 15
A	AB4	4	149	Note (a) below
29	29A1	1	223	See Plate 17
29	29A2	2	255	" " 18
29	29A3	3	269	" " 19
29	29A4	4	293	Note (b) below

Note (a) - Microstructure of 4-minute sample not investigated. See Plate 12 for original structure, item A before quenching tests.

Note (b) - Microstructure of 4-minute sample not investigated. See Plate 16 for original structure, item 24 before quenching tests.

APPENDIX

A review is given below of the following: Thermal study of welds (Etude thermique des Sondures) by Professor A. Portevin and D. Seferian, which appeared in Chaleur et Industrie, Vol. 16, No. 185, September 1935, pages 409-424. A mathematical study of the rate of heating and cooling of a bar melted at one end is shown in curves of Fig. 2 for temperature versus time; the individual curves give the rate of heating for the various distances from the melted end as shown. Fig. 12 gives the curves obtained experimentally for arc welding of mild steel of various dimensions. Fig. 15 gives the plan view of isothermal lines on an arc welded plate of 10 mm thickness. Fig. 18 gives a three dimensional view of the temperature history of the plate surface but does not indicate the isothermal contours of the heat disturbed zone in the plate itself. Fig. 20 shows the cooling rates of acetylene and arc welds.

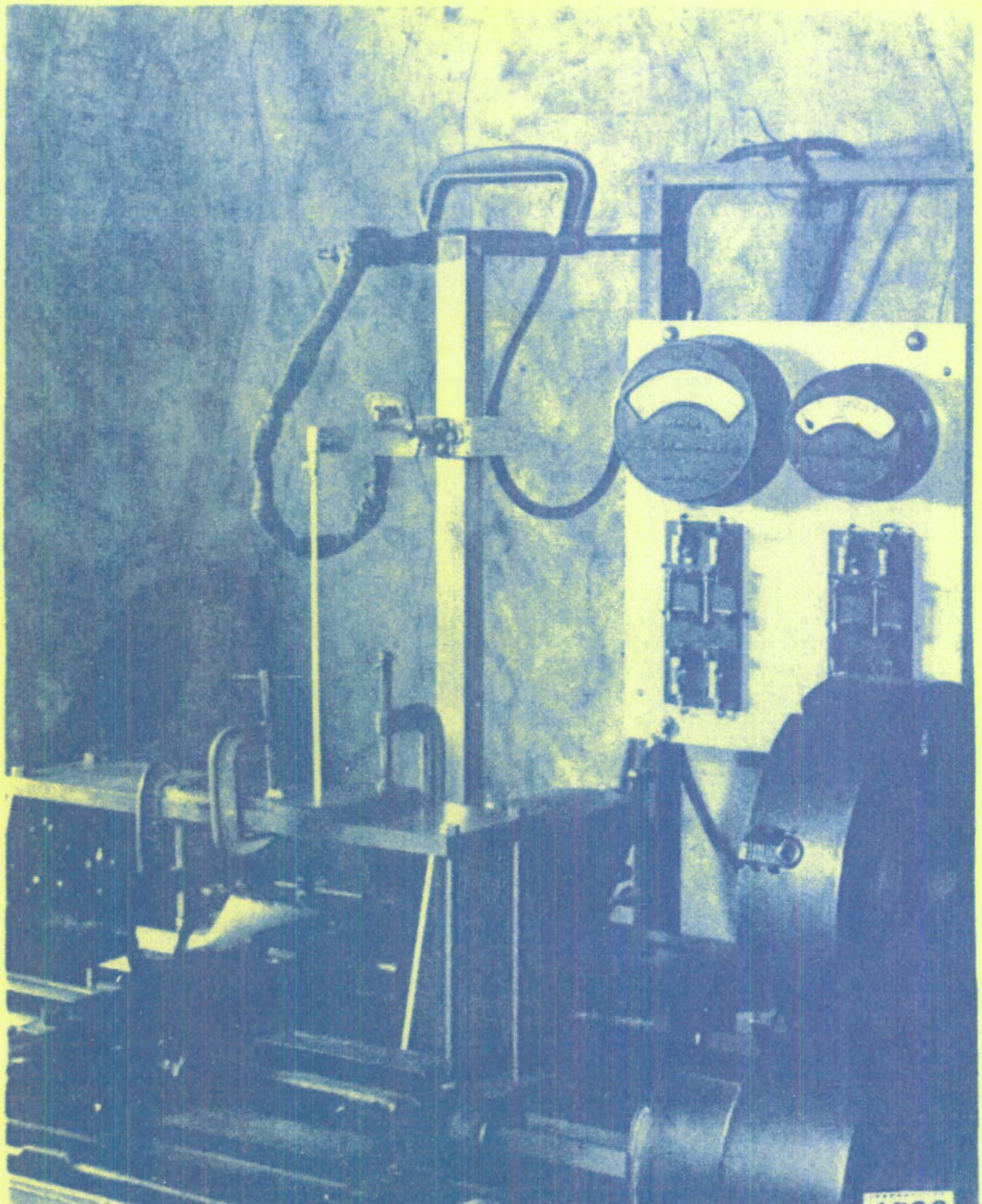
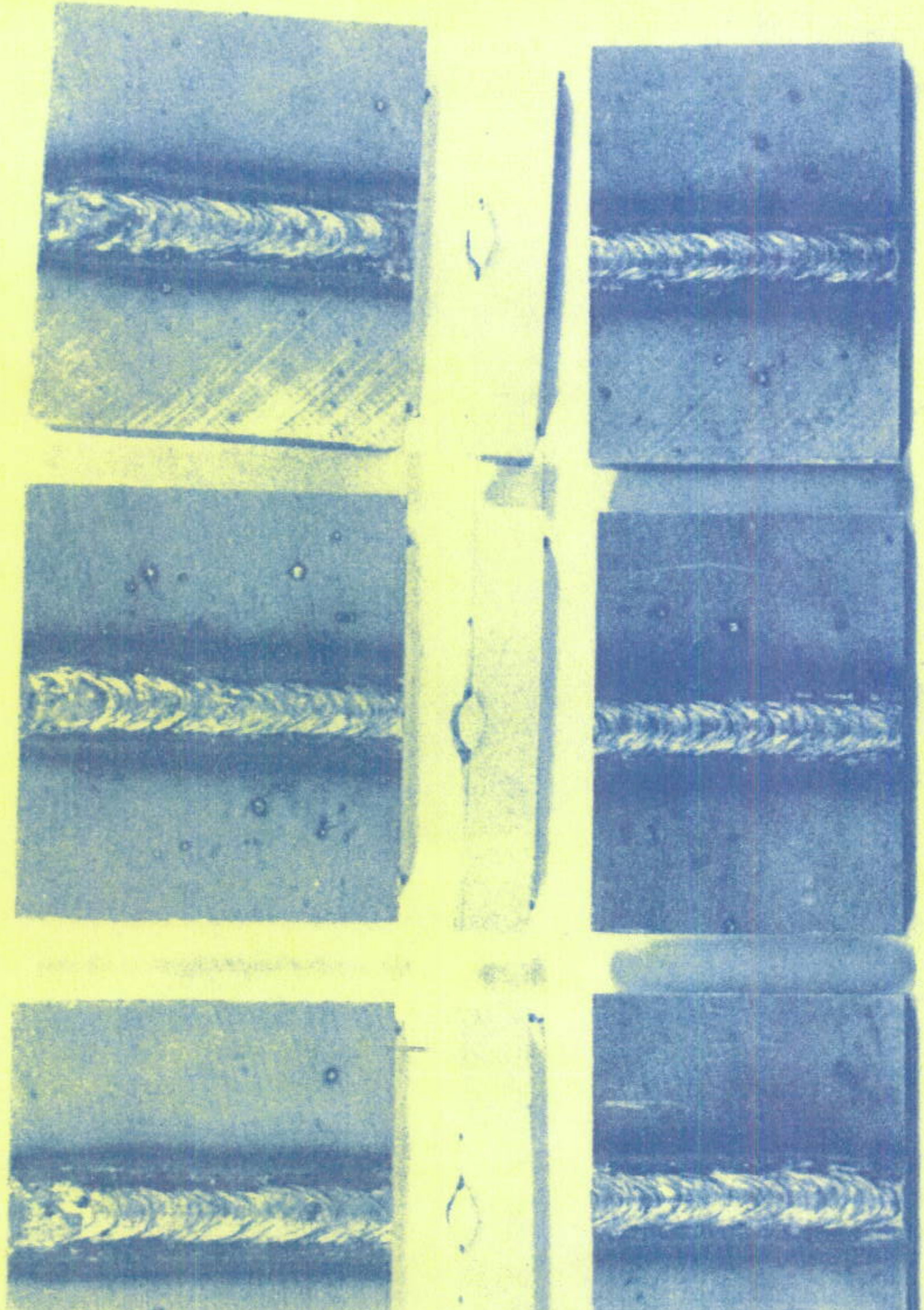
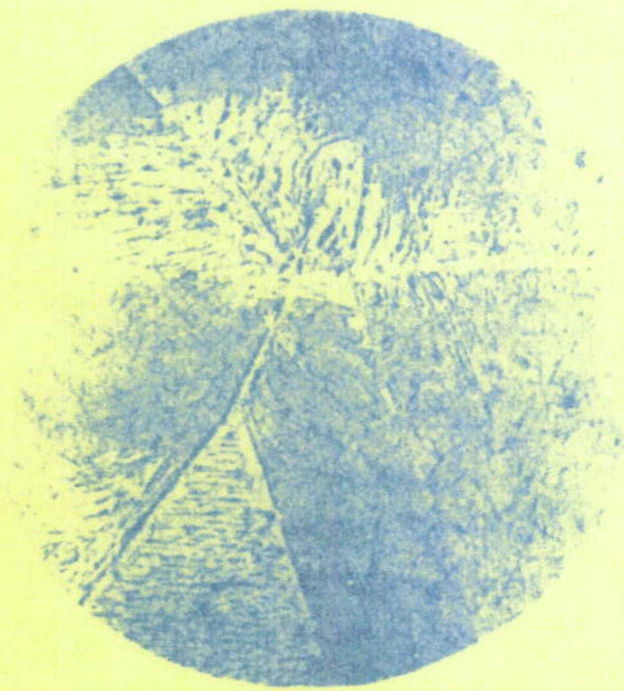


Plate 1

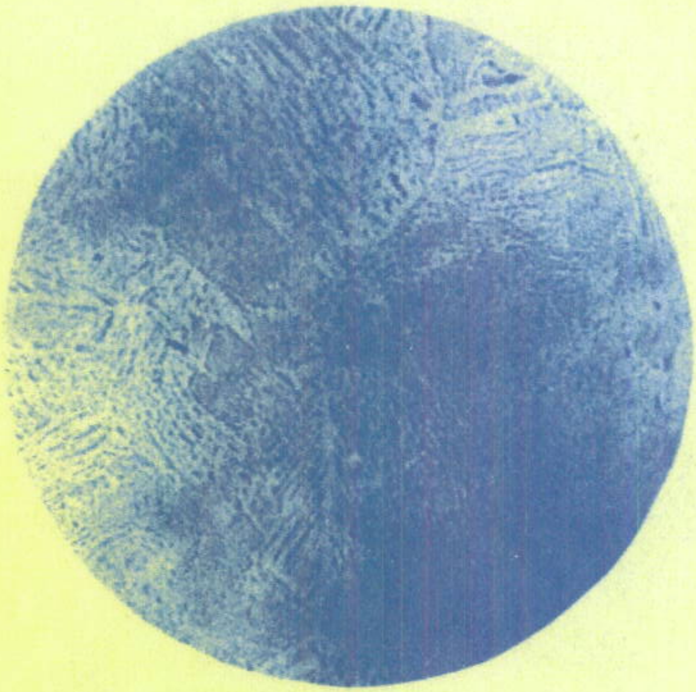


1597

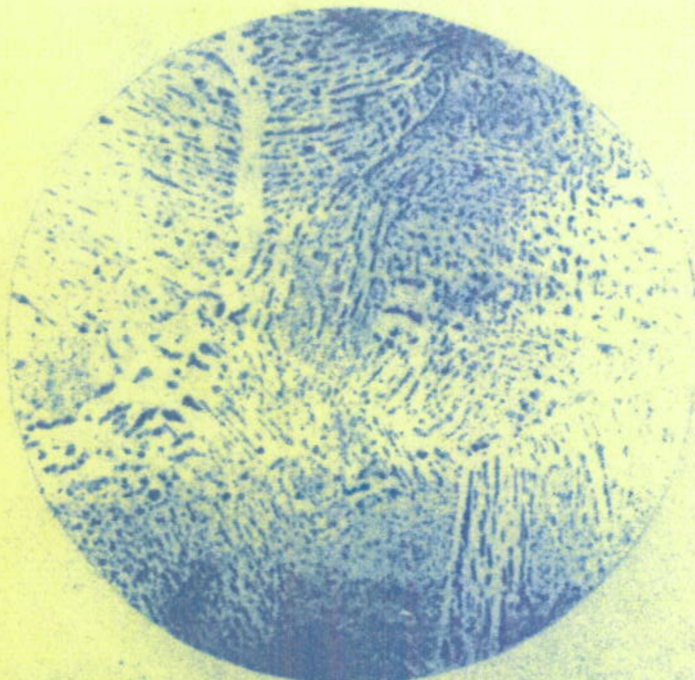
Plate 2



Item A, 1400°C. for 5 minutes, air quench 100X

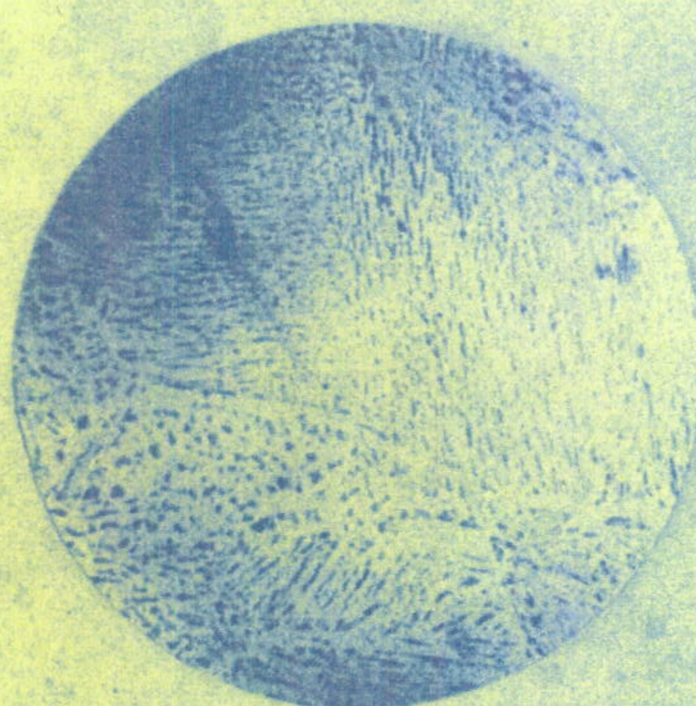


Item A, 1400°C. for 10 minutes, air quench 100X

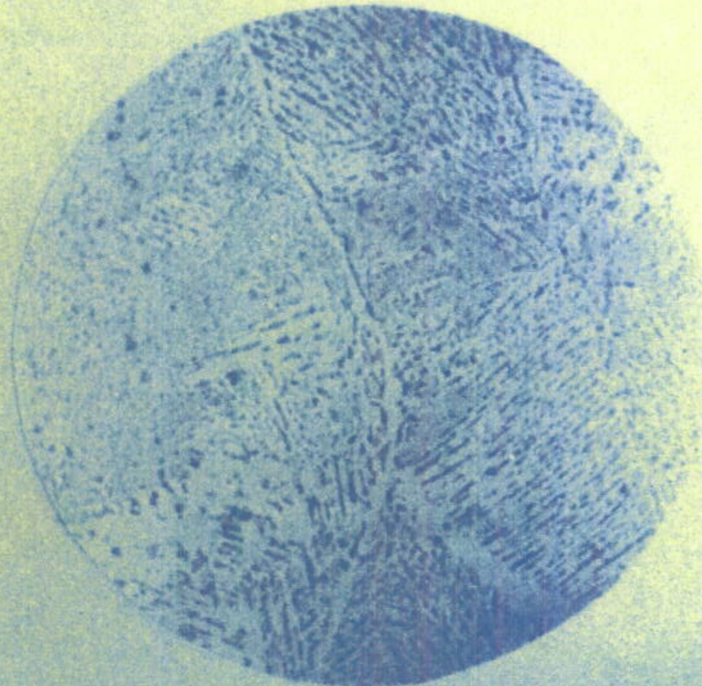


Item A, 1400°C. for 15 minutes, air quench 100X

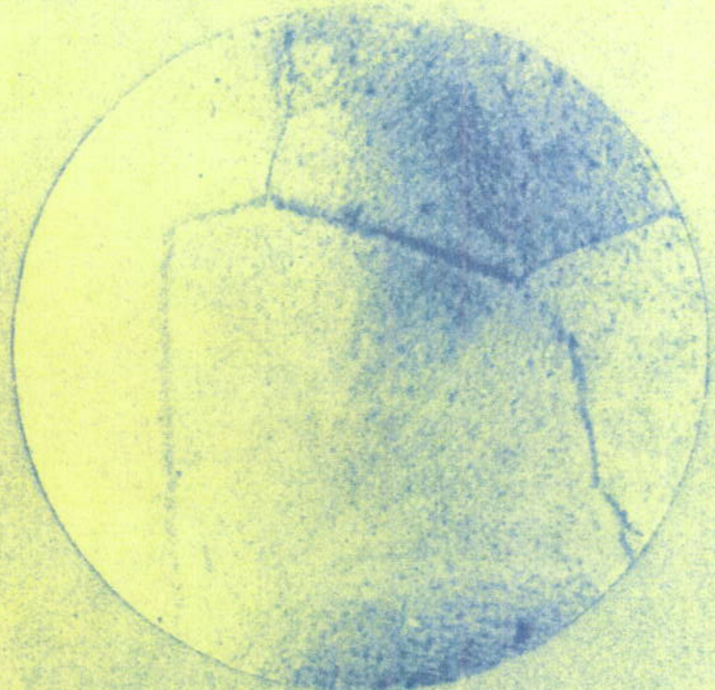
Plate 5



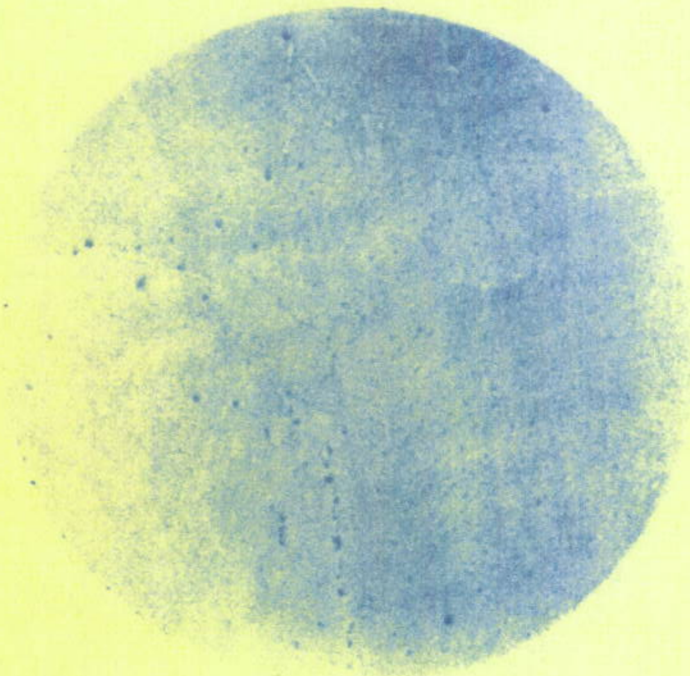
Item A, 1400°C. for 20 minutes, air quench 100X



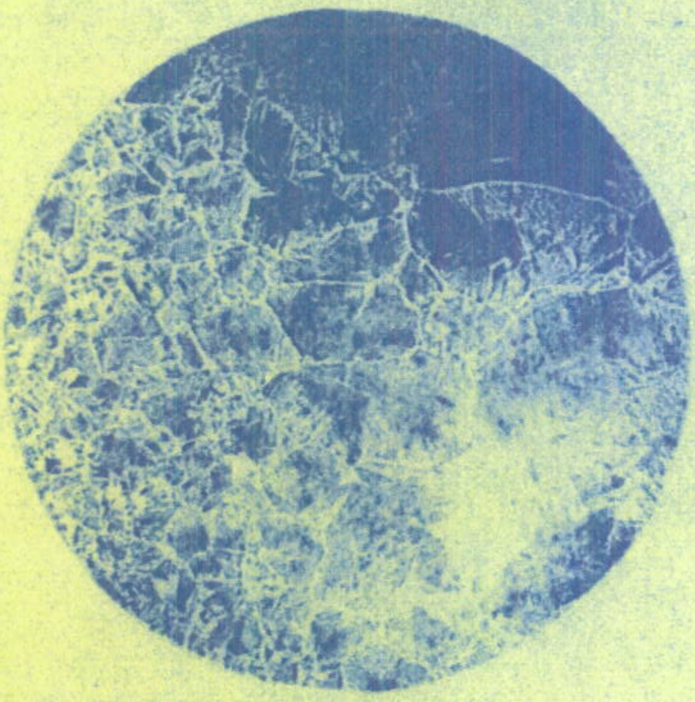
Item A, 1400°C. for 25 minutes, air quench   100X



Item A, 1400°C. for 5 minutes, oil quench   100X

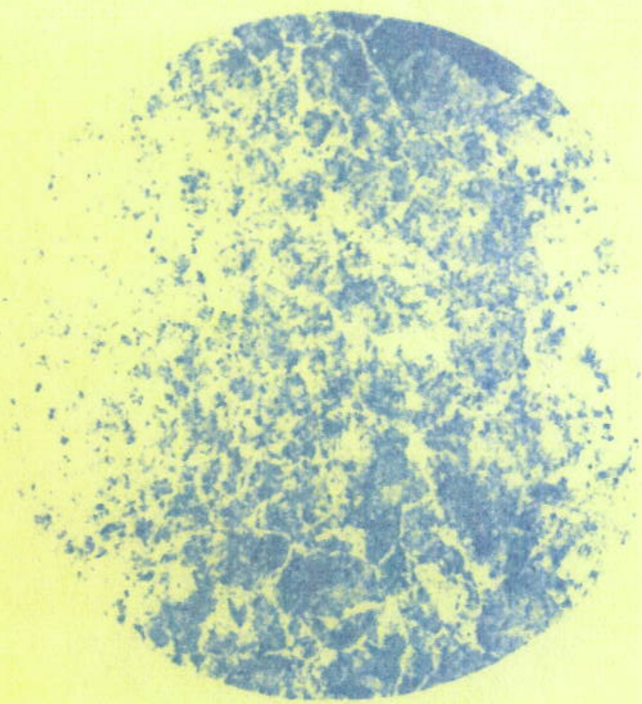


Item A, 1400°C. for 5 minutes, water quench 100X



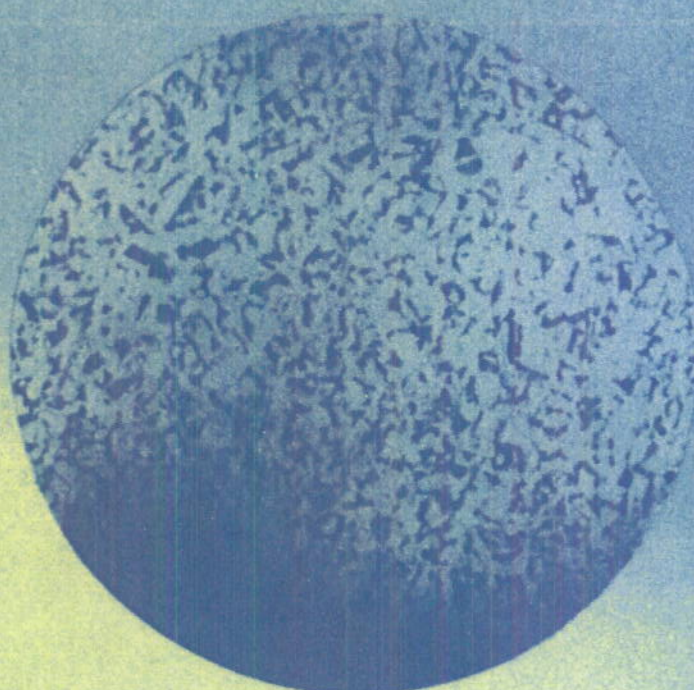
Item A, weld transition zone, manual weld 150 amperes,
27 volts, 3/16" heavy coated electrode.
Speed = 3-1/2 inches/minute.

100X

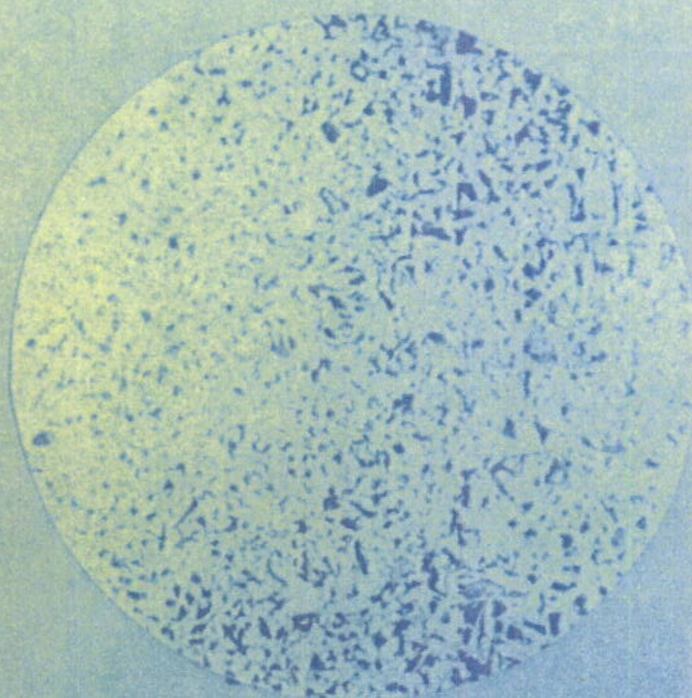


Item A, weld transition zone, semi-automatic machine weld, 190 amperes, 26 volts, 3/16" heavy coated electrode. Speed = 9 inches/minute.

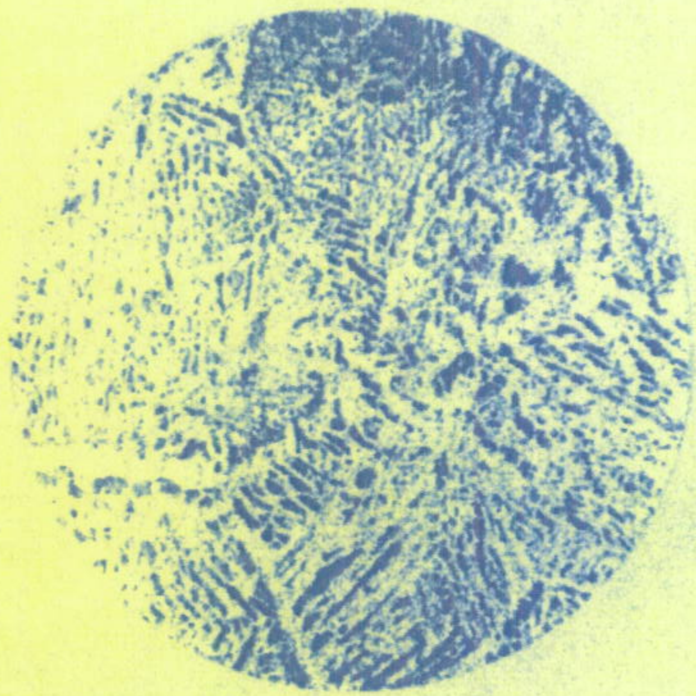
100X



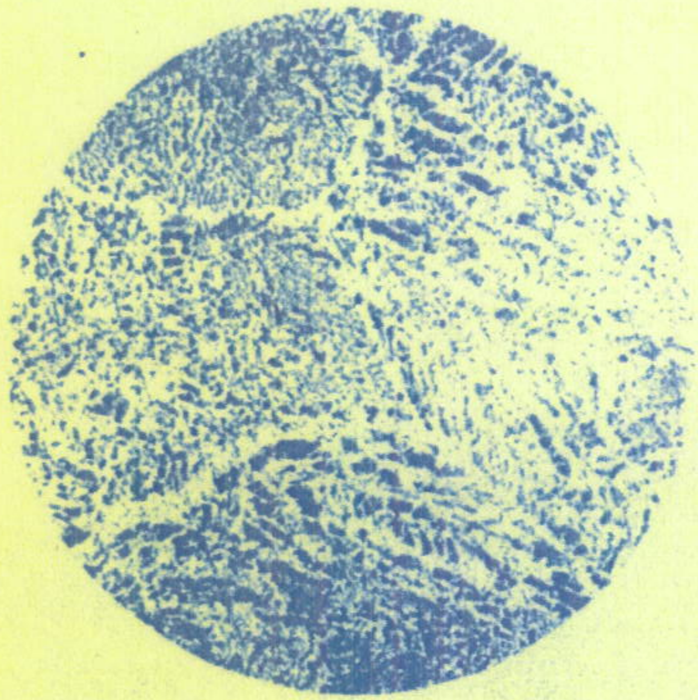
Item A, original Structure 100X



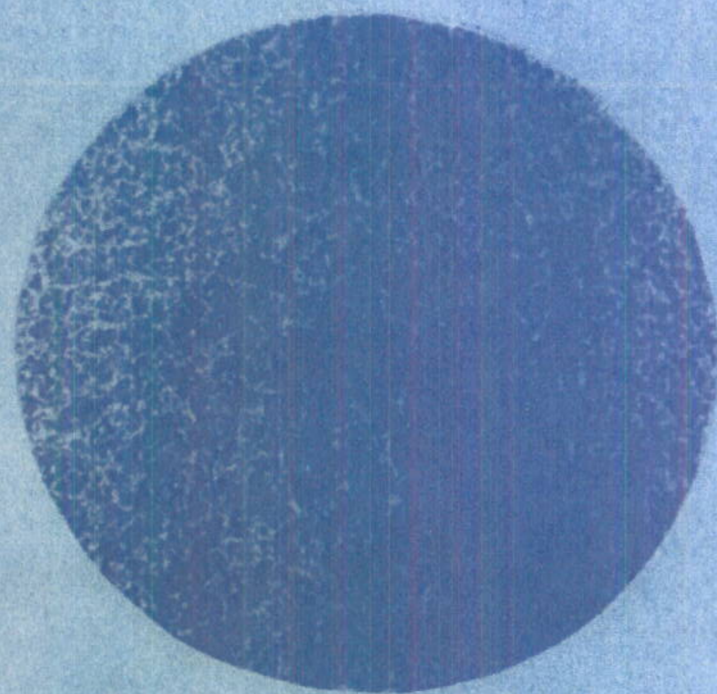
Item A, 1400°C. for 1 minute, air quench 100X



Item A, 1400°C. for 2 minutes, air quench 100X

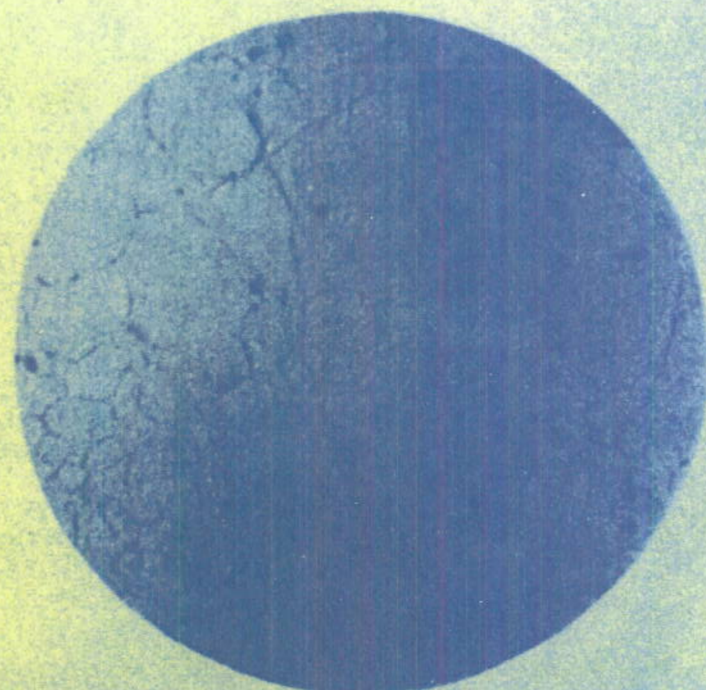


Item A, 1400°C. for 3 minutes, air quench 100X

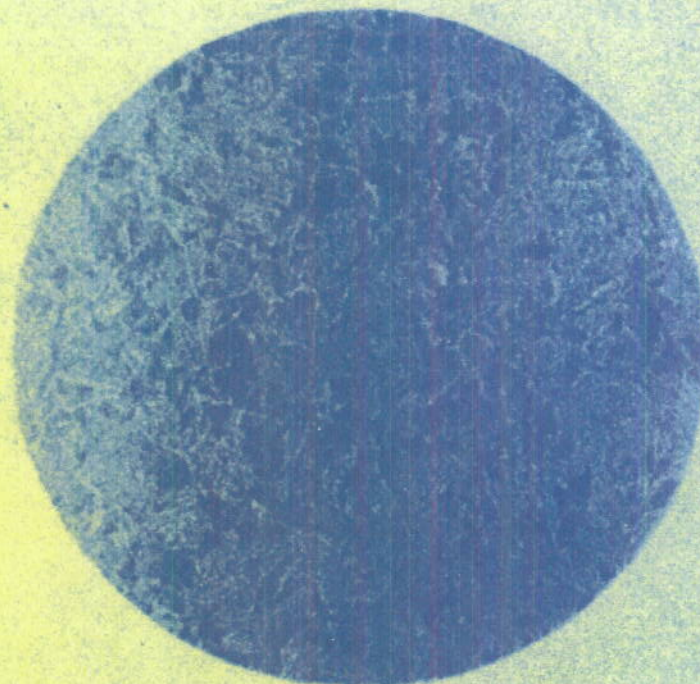


Item 24, original structure 100X

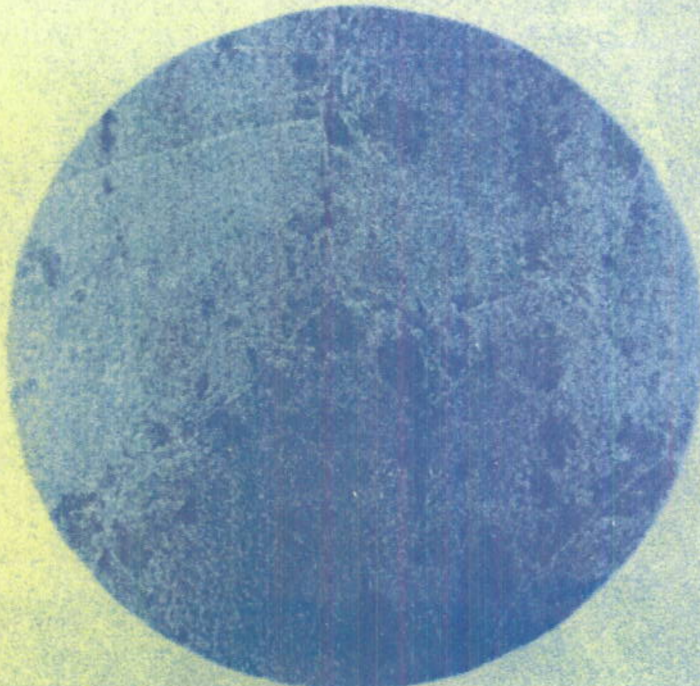
Plate 16



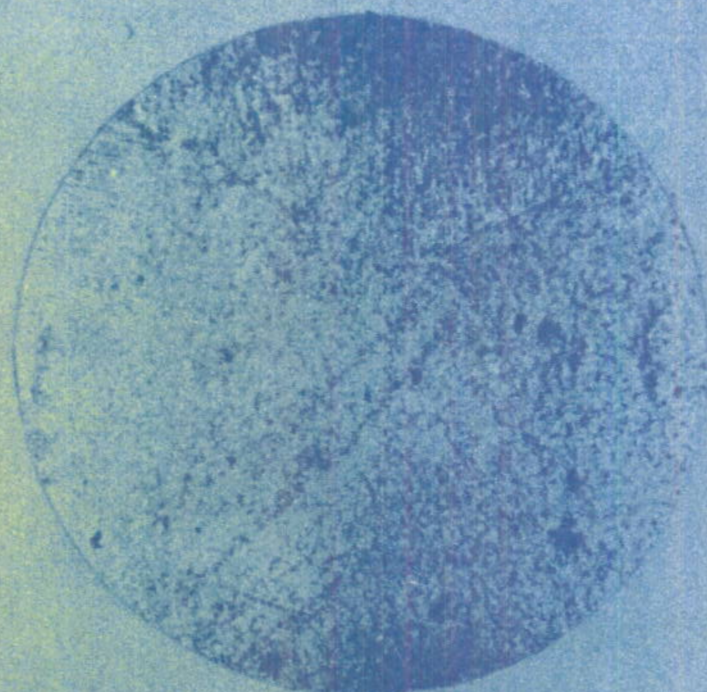
Item 24, weld transition zone, semi-automatic machine weld, 190 amperes, 26 volts, 3/16" heavy coated rod. Speed = 9 inches/minute.



Item 24, 1400°C. for 1 minute, air quench   100X



Item 24, 1400°C. for 2 minutes, air quench 100X



Item 24, 1400°C. for 3 minutes, air quench 100X

Plate 20

dans laquelle :

$$u = \frac{a . x}{\sqrt{2t}}$$

La fonction de Laplace se détermine par les tables (*).

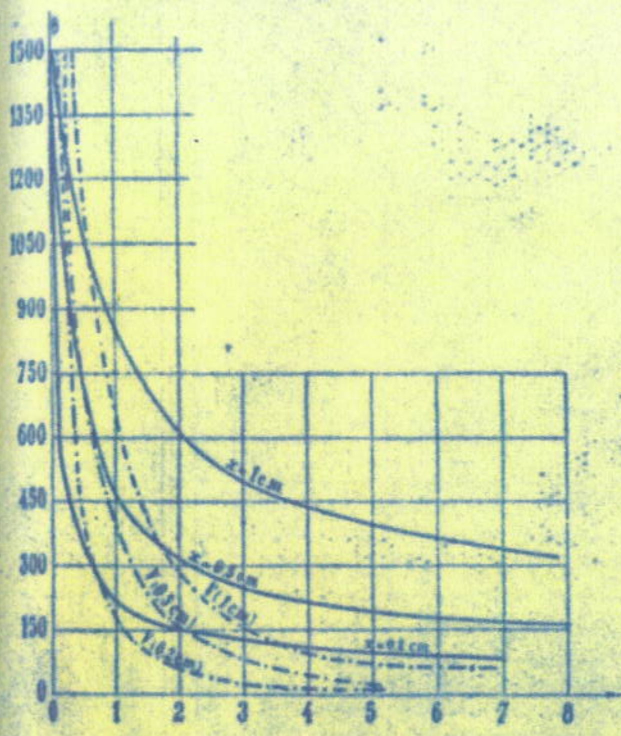


FIG. 2. — *Répartition thermique dans une barre d'acier fondue à une extrémité, à une distance donnée x de la face fondue.*

Application de la formule à l'acier.

$$\theta_0 = 25 \qquad \theta_f = 1500$$
$$\delta = 7,80$$
$$c = 118.10^{-6}$$
$$\kappa = 800.10^{-6}$$

$$2a^2 = \frac{c\delta}{\kappa} = 1,15 \qquad a = 0,76.$$

La relation :

$$\Phi(u) = \frac{2}{\sqrt{\pi}} . \int_0^u e^{-u^2} . du = \frac{\theta - \theta_0}{\theta_f - \theta_0}$$

détermine ainsi la variation de θ pour chaque valeur de x, c'est-à-dire à différentes distances de la face fondue :

Les courbes du diagramme 2 montrent cette répartition thermique dans une barre d'acier.

(*) On peut, en particulier, trouver une table de la fonction de Laplace dans l'ouvrage de M. B. Delteil, *Erreurs et moindres carrés*, page 153. Editeur, Gauthier-Villars (1930).

Les courbes du diagramme 3 montrent l'influence de la nature du métal sur cette répartition. Elles ont été tracées pour le cas du cuivre.

Dans ce cas, les équations différentielles restent les mêmes, la valeur de $a = \sqrt{\frac{c\delta}{2\kappa}}$ seule change ($a = 0,23$) par suite :

$$u = \frac{0,23}{\sqrt{2t}} . x$$

ce qui permet de déduire comme pour l'acier :

$$\Phi(u) = \frac{2}{\sqrt{\pi}} . \int_0^u e^{-u^2} . du = \frac{\theta - 23}{1.083 - 23}.$$

7° Vitesse de refroidissement.

La vitesse de refroidissement se déduit de la courbe $\theta = f(t)$:

$$V = -\frac{\partial\theta}{\partial t} = (\theta_f - \theta_0) \frac{2}{\sqrt{\pi}} . \frac{u}{t} . e^{-u^2}.$$

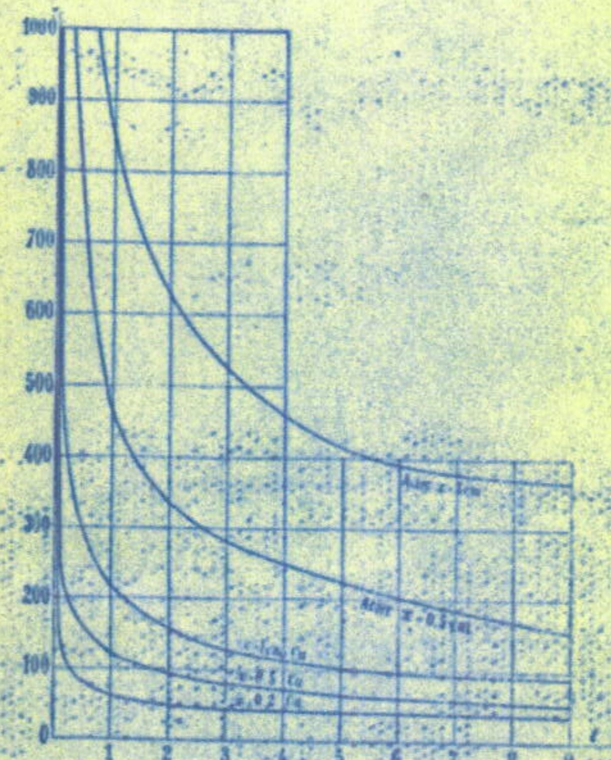


FIG. 3. — *Courbes comparatives de répartition thermique pour l'acier et le cuivre.*

Ces courbes sont représentées pour l'acier sur le diagramme figure 2.

Une valeur intéressante à connaitre est *la vitesse maximum* de refroidissement.

Le maximum de vitesse a lieu pour $\frac{dV}{dt} = 0$ ou

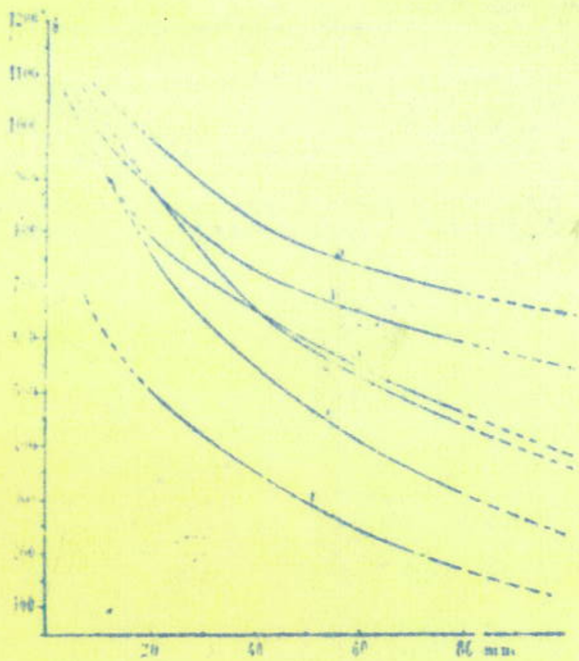


Fig. 10. — *Courbes $\theta_m = f(x)$ pour la soudure oxy-acétylénique du cuivre, pour plaques de 10 mm, température repérée à mi-épaisseur* (a) *et en surface* (b); *plaque de 5 mm* (d); *barre carrée de 10 mm* (c, e); *barre ronde de 5 mm* (f).

Les courbes des figures 9, 10 et 11 donnent l'allure des courbes $\theta_m = f(x)$, des soudures oxy-acétyléniques, exécutées par la méthode « classique », sur des plaques et barres d'acier, de cuivre et d'aluminium d'épaisseur et de formes différentes.

Le diagramme figure 12 se rapporte aux mêmes courbes pour la soudure électrique à l'arc de l'acier doux ordinaire.

2° Courbes de vitesse de refroidissement.

Les courbes de vitesse de refroidissement $V = \frac{\partial \theta}{\partial t}$ ont été construites graphiquement par la méthode des tangentes (*). Pour déterminer un point de la courbe dérivée $\frac{\partial \theta}{\partial t}$ on mène de l'origine des coordonnées, une parallèle à la tangente au point cherché de la courbe $\theta = f(t)$, qui détermine sur une droite quelconque parallèle à l'axe des θ un segment dont la valeur est : $\frac{\partial \theta}{\partial t}$. La projection de ce segment sur l'ordonnée du point de la courbe donne un point de la courbe des vitesses de refroidissement cherchée.

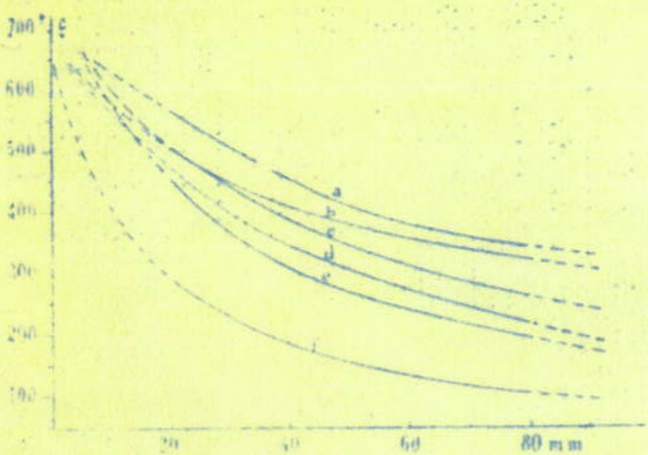


Fig. 11. — *Courbes $\theta_m = f(x)$ pour la soudure oxy-acétylénique de l'aluminium — (mêmes désignations que la fig. 10).*

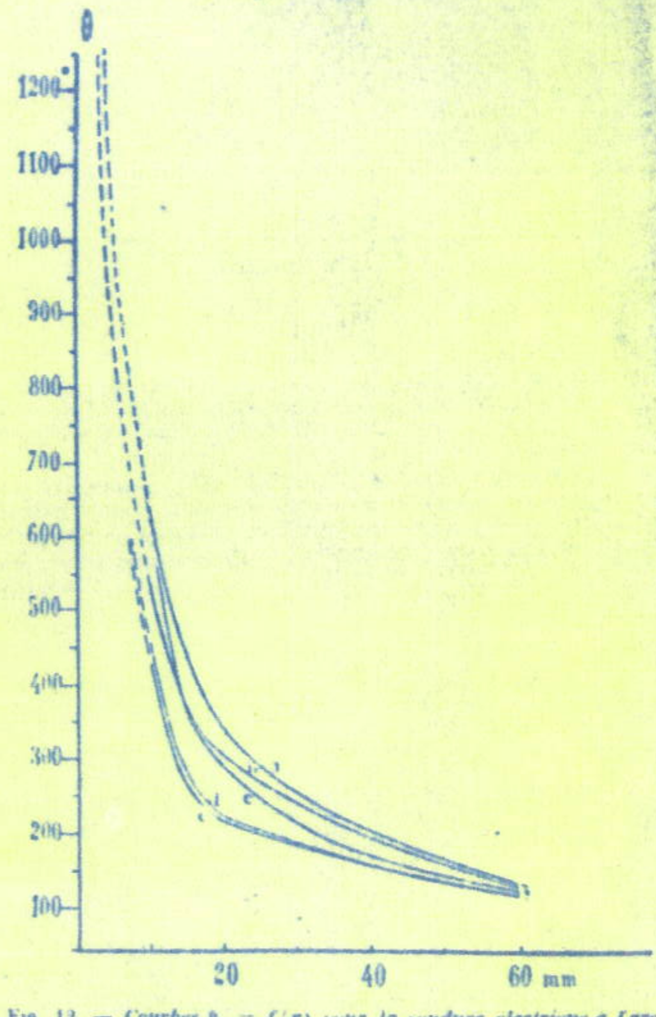


Fig. 12. — *Courbes $\theta_m = f(x)$ pour la soudure électrique à l'arc de l'acier doux, sur plaque de 10 mm, repérage de température à mi-épaisseur* (a) *et en surface* (b), *plaque de 5 mm* (c) *et barre carrée de 10 mm* (d, e).

3° Étude des courbes isothermes.

Le calcul montre que l'ensemble des courbes isothermes est une famille de paraboles (réelles ou dégéné-

(*) Méthode utilisée en particulier par M. P. Chevenard. Voir *Analyse dilatométrique des matériaux*. Dunod. Paris. (1929).

rées) enveloppes des isothermes pour une position définie du chalumeau ou de l'arc, fonction de la vitesse d'avancement. Les courbes enveloppées sont des ellipses qui seront entièrement déterminées par leurs deux axes.

Le grand axe d'un isotherme quelconque θ est donné par la courbe $\theta = f_o(t)$ pour la ligne de soudure ; sa

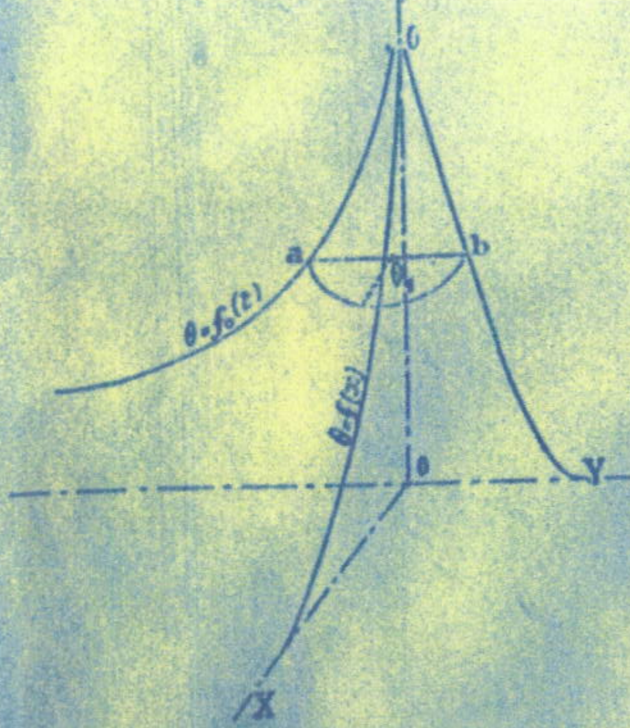


FIG. 13. — *Méthode de détermination des isothermes.*

longueur est égale au segment (ab), (fig. 13), pour la valeur de $\theta = \theta_1$. Le petit axe est déterminé par la courbe $\theta = f(x)$.

La première courbe $\theta = f_o(t)$ se déduit par extrapolation des courbes $\theta = f(t)_x$, tracées expérimentalement pour différentes valeurs de x. Cette extrapolation a été faite en traçant les courbes isochrones, pour les temps t, $t + \varepsilon$, $t + 2\varepsilon$... jusqu'à leur rencontre avec le plan $x = o$ (plan de la soudure).

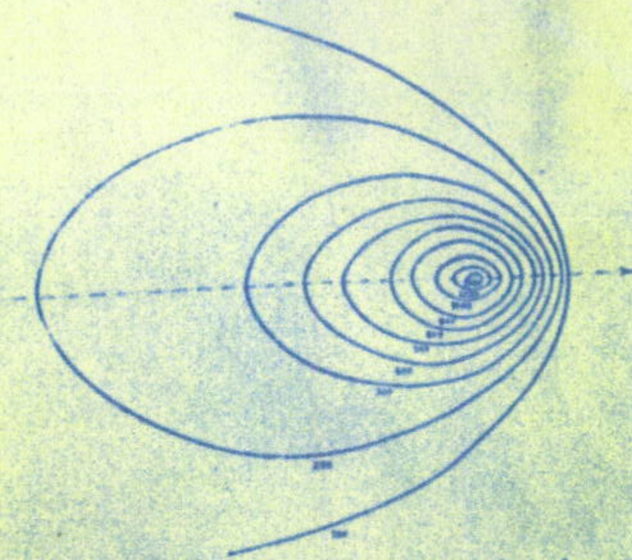


FIG. 14. — *Isothermes à un instant donné, cas de la soudure oxy-acétylénique (méthode classique) de l'acier doux (plaque 10 mm). Projection sur le plan de la plaque.*

Le diagramme (fig. 14) représente les ellipses isothermes d'une soudure oxy-acétylénique (méthode classique), en un point quelconque de la ligne de soudure ; nous pouvons tirer tout de suite les conclusions suivantes :

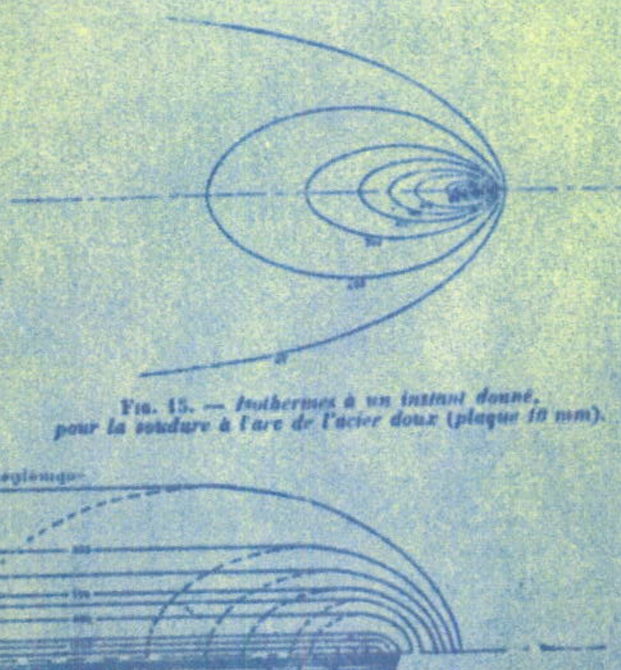


FIG. 15. — *Isothermes à un instant donné, pour la soudure à l'arc de l'acier doux (plaque 10 mm).*

FIG. 16. — *Enveloppe des isothermes pour les soudures oxy-acétylénique et électrique à l'arc, entre deux instants donnés ; le régime stationnaire a été atteint.*