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ABSTRACT

Methods are described for reproducing the conditions existing in the transition zone of a weld by heating small samples to high temperatures and quenching in liquid baths. The heat treatment, called "weld-quench" in the report, gives fair reproducibility and for individual materials quenched, is usually within 90% or better of attaining the maximum hardness in the transition zone of welded plates. Further perfection of technique and equipment, especially automatic temperature control and stirring of the quenching baths, gives promise of improving the results still further.

Exact temperature-time curves for the thermal cycle undergone by metal in the transition zone have been experimentally determined, it is believed, for the first time. Several curves for this thermal cycle are presented. The suggestion is made that further investigation of temperature gradients and thermal cycles for various degrees of preheat, speeds of welding and varying plate mass would be desirable. The results of such an investigation are visualized as the determination of minimum preheat and maximum welding speed from the values given by samples of the materials subjected to weld quench tests.

It is believed to be the first time in the history of arc welding that a method of heat treating has been presented which reproduces synthetically the metal in the transition zone of an arc weld. The same novelty is claimed for the curves of the welding thermal cycle.

The objective originally set by the Bureau of Engineering when the problem was initiated is believed to have been reached, thus making possible a determination of weldability of various steels with a simple quenching test which can be made at low cost. The report describes results which show, unquestionably, that steels of good weldability can be picked out by tests on the weld quench samples as well as steels known to offer difficulty in welding unless specially treated. It is easily within the province of the test to enable values of per cent hardenability and absolute hardness increase to be obtained from the unbroken ends of the impact samples before and after heat treatment; thus the entire information as to weldability may be obtained without resort to a single welding test.

AUTHORIZATION

1. This investigation was authorized by BuEng.let. JJ46-1/L5(4-2-Ds) of 4 April 1935.

2. A first partial report, NRL Report No. M-1258 of 1 April, 1936, stated the problem in detail and discussed early progress of the work.

3. A second partial report, NRL Report No. M-1303 of 14 September, 1936, described additional progress made during the investigation.

STATEMENT OF PROBLEM

4. The problem is most simply stated as an investigation of the physical and mechanical properties of the transition or heat disturbed zone of parent metal next to the weld bead, the weldability of the parent metal being defined for the problem as the quench sensitivity (hardenability) and grain growth susceptibility as they affect the mechanical properties.

5. The ultimate aim of the research is to correlate grain growth and hardness with toughness as determined by the impact test in order to evaluate the probable service behavior of welded steels. The toughness (impact resistance) of the transition zone metal for the various conditions below is to be desired for:

(a) Maximum disturbance of the parent metal on depositing the first bead of a multiple bead weld and the single bead fillet weld which would include the phenomenon of fissuring.

(b) The extent to which a subsequent bead repairs the disturbing effects of the first bead. Here we are concerned with grain refinement, reduction of hardness and production of a more desirable microstructure.

(c) Maximum disturbance to the parent metal on depositing the last bead of a multiple bead weld. Here we are concerned with the mechanical properties of the disturbed parent metal since without stress relief, or annealing treatment, it will be put into service in the condition in which the welding process left it. This is also the case for the single bead fillet welds under (a).

(d) Corrective measures to limit the disturbance by means of:

(1) Choice of parent metal composition.
(2) Preheat.
(3) Choice of welding speed, electrode, welding current, etc.

(e) Corrective measures such as subsequent heat treatment to repair the disturbance after it has occurred.

6. For the present the investigation limits itself to the solution of (a), (c), (d) by means of a heat treatment to reproduce as closely as possible the parent metal in the disturbed zone in order to determine its probable mechanical properties.

KNOWN FACTS BEARING ON THE PROBLEM

A. Literature Sources

7. The French article by A. Portevin and D. Seferian referred to in NRL Report No. M-1258 has been translated by the writer and appears in the appendix. A review of the literature on the effect of the welding heat in the transition zone is in preparation.

B. Experimental

8. From the research reported in NRL Report No. M-1303 it was indicated that the average grain size developed in a half-size (.197" x .394" x 2.0") Charpy impact specimen, heated for 1-1/2 minutes at 1400°C., was of a fair order of agreement with the maximum found in the transition zone. The duplication of microstructure had not been considered in previous reports since the research had not yet developed a suitable quenching cycle to reproduce in the quenched samples the maximum hardness of the transition zone.

9. The quench tests reported in the previous report were made on Items 1 and 2 with carbon .17% and .25%, respectively. Both steels are of low hardenability and quenching in air was shown to produce a hardness slightly inferior to maximum transition zone hardness for the items.

METHODS AND MATERIALS

A. Weld Quench Tests

10. For further investigation of the quenching cycle to duplicate transition zone hardness, Items 2 and 22 were quenched from the high temperature and later Items 3, 17, 18, 19 and 24 were included when the research had indicated a successful direction for the quenching methods used.

11. The first test made with the half-size Charpy sample was the determination of the heating and cooling rate for an air quench from 1400°C. A Pt-Pt RL thermocouple was pushed into the bottom of a hole in the side of the sample, item 2, terminating in the center of mass. The thermocouple wires were insulated over the entire length. The e.m.f. of the couple was determined on a Leeds and Northrup potentiometer, while heating to 1370°C. in the steel block and during air cooling. The readings on the steep portion of the curve, Plate 8, are not obtained as accurately as during cooling, but the time for the sample to reach furnace temperature is easily defined.

12. This test established the accuracy of the prediction made in the previous report that 1-1/2 minutes heating in the steel block would be required for the samples to reach furnace temperature. A basis for standardizing subsequent quench tests at 1-1/2 minutes in the furnace was thereby provided. The next procedure was to attempt to increase the hardness of the samples by quenching in a blast of air. This was unsuccessful due to ignition of the sample. Other methods of quenching in carbon dioxide and between two cold, steel plates were also unsuccessful in raising the hardness.

13. The next step was the use of quenching baths maintained at constant temperatures. A lead bath quench and other quenching baths of fused caustic soda (NaOH) were used, the latter being introduced in order to overcome the disadvantages of the lead bath as regards oxidation of the bath surface, adherence of a lead film and drops of lead to the sample, and also

to provide a less drastic quench. For quenches below 318°C. down to 185°C. a 40 Mol per cent addition of KOH was made to the NaOH in order to bring down the melting point of the NaOH (318°C.) to 185° for the KOH-NaOH mixture. A few quenches were made in oil after a first quench at higher temperature in the NaOH bath. A final series of quench tests was made with three samples of each item quenched under the same condition (Table No. 3), the condition being determined by the optimum realization of the objective of transition zone maximum hardness in previous tests of one sample each (Table No. 2, parts 2 and 3). In these final tests there were included several commercial steels especially designed for good welding properties in order to determine comparative loss of impact value with heat treatment.

14. It will be noted that the report covers quench tests for three types of heating: (1) in the graphite resistance furnace as was done for samples treated for the previous report; (2) in the Hayes, Globar furnace which became available through purchase and in which samples were first heated in a steel block maintained at furnace temperature; (3) in Hayes, Globar furnace without the use of a steel block for heating. The latter was decided upon when it was found that the steel block resting on the Carbofrax hearth was reacting with the refractory. A test with a No. 40 gauge Pt-Pt Rh thermocouple indicated that 90 seconds were again required to heat the half-size Charpy to 1350 - 1365°C. It is believed that in the case of heating samples in the graphite resistance furnace the efficiency of heating by radiation was less than in the Hayes furnace using a protecting atmosphere on the carburizing side of neutral (luminous flame), thereby explaining the fact that in the latter case the steel block was unnecessary.

15. A method was then developed for determining the thermal cycle for the weld transition zone during the welding operation. A Pt-Pt Rh thermocouple, No. 40 gauge wire, was spot welded into a 2 mm drilled hole, so placed with respect to the weld that the bead of the thermocouple was in the transition zone .08" below the plate surface. Two plates of Item 22 and one of Item 4 were welded at 6 inches a minute, using 3/16" grade EA, Class 2 electrodes at 180-190 amperes and 25-27 volts. The change in temperature of the thermocouple bead was recorded on a motion picture film in the camera taking pictures of a millivoltmeter connected to the couple. The films were developed and meter readings obtained from the projection of the pictures were put into the curves shown below, Plates 13,14. Plate 22W5 and 22W6 were then sectioned to find out where the bead of the thermocouple was at the time the temperature was recorded. This was necessarily a post mortem operation, since the couples were originally positioned so as to be .03 - .05 inches from the fusion line but due to warpage of the electrode or other causes, the travel was slightly off center. The position of the fusion line of the above samples was predicted by mapping out the weld contour of a W3 weld sample which was of the same material previously welded under identical conditions. The results of the sectioning of the samples after welding are discussed below under the heading of "Data Obtained".

B. Welding Tests.

16. The welding tests here reported were made in accordance with the standard described in NRL Report No. M-1303; e.g., plates 6" x 3" of various thickness as shown in Table No. 1. The plates of rolled steels were rough surfaced to remove scale and were welded with a bead along the 6" length in the middle of the plate. In all cases, the 3/16" grade EA, Class 2, heavy-coated electrodes were used with 180-190 amperes, 25-27 volts, at a speed of

6" a minute. The analyses of the materials welded are shown below, page 5, and the microstructures are shown in Plate 1 for a magnification of 100.

17. Progressive hardness surveys were made on a 1/2" section cut from the welded plate, transverse to the bead, at a distance of 1/2" beyond the middle of the plate toward the crater where the weld was completed. The sections were polished, etched, and indented with the diamond pyramid at a load of 10 kilograms, as was described in Report No. M-1303.

18. The materials used for the mass effect tests were Items B and No. 36, 1-1/2" and 1-7/8" original thickness, respectively, which were cut to various thicknesses given in the data below. The welding tests on these materials were made so as to deposit a bead on the outside face of the original bar in every case. The plates were rough surfaced to remove scale before welding.

19. The plates of cast steel, approximately 3/4" thick, were supplied with sandblasted surfaces which were cleaned with CCl_4 and welded on the sandblasted surface. The plates were originally cast to 6" x 9" size which were cut to provide three 3" x 6" plates for welding tests.

DATA OBTAINED

20. Table No. 1 summarizes the results obtained in the hardness survey of 1/2" sections cut from the 3" x 6" welded plates. The results reported for Items 03, 4, 25, 26, 35 are for materials it was intended to include in the previous report but which were received too late. It will be noted that Item 4, .380" thick, is less than the standard, 1/2" thickness for the other welding tests, and the hardness values given in the table should be replaced by the corrected probable value, in parenthesis, when comparisons are to be made. The value of probable, maximum hardness for Item 4 was obtained by drawing a line parallel to the linear curve of hardness versus thickness obtained for Item B, Plate 11. All corrected values for Item 4 were carried through from the corrected maximum hardness and are given in Table No. 1 in the parentheses. The value given in Table No. 1 for weld hardness is the maximum for three indents in the weld along the same line as the indents in the transition zone. One indent was made in the center of the weld and two others on either side .05 to .07 inches from the fusion line.

21. The curves showing progressive hardness values across the transition zone are given for the 1/2 inch thick rolled steels in Plate 9. The curves for mass effect tests are purposely plotted close together in Plate 10 in order to bring out the change in contour with varying thickness. Hardness versus thickness curves for the mass effect tests are given in Plate 11. The welding tests for the cast steels were made in duplicate and are reported in Table No. 1 for each test made and the average of the two tests. The progressive hardness curves are given for only one of the duplicate cast steel plates in Plate 12 since the two curves were practically alike on contour.

22. Tables No. 2 summarize the quenching test results for the half-size Charpy samples heated at high temperature for 1-1/2 minutes and quenched by various methods as shown. The table is divided into several parts which represent the various stages through which the investigation passed in arriving at the results shown progressively in the table. Table No. 3

CHEMICAL ANALYSES

Item	C	Mn	Si	Ni	Mo	
03	.35	.68	.23			(Silicon killed, plain carbon steel, rolled.
4	.44	.65	.24			(
25	.19	.40	.18	3.63		(Rough forged, Ni steels.
26	.23	.48	.19	3.55		(
35	.27	.69	.20	2.31		(Ni steel, rolled.

<u>Mass Effect Tests</u>

Item	C	Mn	Si	Ni	Mo	
B	.26	.64	.20			(Grade M, null plate, 1-1/2" thick.
36	.27	.69	.21	2.30		(Ni steel, 1-7/8" thick.

<u>Cast Steels</u>

Item	C	Mn	Si	Ni	Mo	
51	.31	.55	.42			(Cast steels. Casting 6" x 9" x 3/4".
52	.14	.54	.54			(Heated, after casting, to 1600-1650°F.
53	.26	.63	.48			(for 1 hour, air cooled. Reheated to
54	.43	.61	.44			(1200°F., held 1 hour and furnace
55	.25	1.26	.64			(cooled. Surfaces of plates were
56	.40	.73	.48		.62	(sandblasted.

summarizes results obtained by quenching three samples of the same item according to the quench procedure of Test No. 5 of Table No. 2, part 3; here the extent of reproducibility of impact value and hardness is indicated for a series of samples. Table No. 4 takes the values of impact for the quenched samples of Table No. 3 and compares them with impact value of the original material in the "as received" condition. The values for per cent of original impact after heat treatment given in Table No. 4 are of primary interest in evaluating the weldability of the materials in terms of toughness, together with values obtained for per cent hardenability and absolute increase in hardness.

23. The curves of Plate 17 summarize all the results on hardness surveys of 1/2-inch thick welded plates of rolled materials investigated thus far. To draw these curves the data obtained in the previous partial report were used, together with the data on additional steels included in the present report. The chemical analyses have been included below the curves.

24. The photomicrographs included in the report are indexed on page (a) and may be referred to for the microstructures shown.

DISCUSSION OF RESULTS

(a) Facts Established

25. The data from the thermal cycle curves, during the welding operation, of Plate 13 for samples 22W5, 22W6, and 4W5 are of prime interest in establishing the heating and quenching rate of the transition zone in the neighborhood of the fusion line as summarized in Table No. 5. The heating rate of 11 to 11-1/2 seconds to reach maximum temperature in the transition zone for a 1/2" thick plate is easily seen to be impossible of realization for the weld quench by the present method of heating the samples in a furnace maintained at the desired maximum temperature. The source of heat for the transition zone, the arc and weld metal, is at a temperature around 7500°F. and therefore this rapid heating to 1400°C. is possible. Other methods of rapidly heating the half-size Charpy samples that are being considered for future tests are high frequency induction and high amperage resistance heating. However, the information obtained from a comparison of impact values as reported in Table No. 4 may be sufficient to weed out all steels of poor weldability and indicate realtive merits of the weldable steels.

26. The maximum rate of cooling is shown in Table No. 5 to increase with the maximum temperature attained for the duplicate tests 22W5 and 22W6, thus checking the theoretical results of Portevin and Seferian shown in Fig. 20 of the translated article in the appendix. However, the cooling rate through 725°C. is less for the part of the transition zone closer to the fusion line by .02" - .03" (22W6). As a consequence there is a change in the slope of 22W6 at 625°C., presumably representing a transformation, while in 22W5 for the higher rate of cooling through 725°C., an inflection point shows definitely only on reaching 410-400°C. See Plate 14 for curves of temperature vs. log. time. This is interpreted as indicating that the nearer the transition zone area is to the fusion line, the more rapidly and effectively does it respond to the withdrawal of the arc in its travel, giving a higher initial rate of cooling. But also, the nearer to the fusion line the greater is the retardation of cooling after the initial drop, due possibly to (1) heat

traveling back from the arc, (2) heat from cooling weld metal, or (3) blanketing effect of slag coating over deposit area.

27. This brings up the question of the causes for the flattening out of the hardness contours plotted for the progressive hardness surveys or as occurs in many cases, a greater hardness being obtained .02 inches (approximately) from the fusion line than immediately adjacent to it. The lower cooling rate through the critical point for the material .02 inches (approximately) from the fusion line would explain the occurence of maximum hardness at a distance slightly removed from the fusion line (see hardness contours plotted on Plates 6 and 7 of previous report). This has previously been explained in the literature on the basis of diffusion of carbon or alloy into the weld metal.

28. It should be noted that all quench tests in Table 2, parts 1 and 2, were made previous to obtaining the thermal cycles for the actual welding operation. The conditions of the tests were progressively changed on the basis of results obtained on examination of the micrographic features of the quenched samples as compared with the transition zone of the corresponding welded material. Part 1 of Table No. 2 gave convincing evidence of a quenching rate in the weld transition zone such that steels of higher carbon or alloy content would have a split transformation and if the transformation at the higher temperature were not delayed too much we should expect to find in the transition zone products of both the high and low temperature transformation. Examination of the transition zone of Item 4W3 gave proof of the split transformation (carbon content of .44%) since both pearlitic and acicular transformation products were found. The tests of Table No. 2, Part 2, were then made and it can be seen that the correct cooling rate through the upper transformation range had been attained and that the correct cooling rate through the lower transformation range was being approached. As soon, however, as the quenching curves for the 22W5, 22W6, and 4W5 samples were available, it became evident that the lower transformation-cooling rate must be less drastic. The tests made for Table No. 2, Part 3, then followed, the choice of conditions being supported by facts established in previous quench tests, micrographic studies of quenched and welded samples, and in the thermal cycle curves for the welds. With the practically complete success obtained in Test 5 of Table No. 2 showing almost 100% attainment of the objective aimed at (with the exception only of Item 22 which is discussed later in the report), it was decided that final proof of success must depend upon reproducibility of results obtained in Test 5 above and close checking of values for at least three samples of the same material. These results given in Table No. 4 indicate a high order of reproducibility and again almost 100% attainment of transition zone hardness. Still further improvement in reproducibility of weld quench results and in attainment of transition zone maximum hardness can be expected when the automatic temperature controls, which we have on order, have been installed to regulate the quenching bath temperatures. Stirring equipment in each bath will be used along with automatic temperature control. The comparison of impact values before and after weld-quench, heat treatment in Table No. 5, which establishes the facts in respect to probable mechanical properties will be discussed later in this report, since it is desirable at this time to review the facts established by the microstructures.

29. The continuous micrographs at a magnification of 500 shown in Plate 2 are purposely mounted side by side in order to aid in comparing the materials for the different modes of transformation effected in them as a function of carbon and alloy content and of distance from the fusion line. Consideration of the latter factor alone for Item 4W3 led to a prediction

of the probable quenching rate and how it changed with distance from the fusion line, before the actual thermal cycles were obtained, and the accuracy of the prediction is attested by the results obtained in Table No. 2, Part 2. Since the micrographs are at 500 magnification, a ruler can be laid down and the distance from the fusion line can be measured on the basis of 5 inches = .01 inch. The fusion line at this magnification cannot be seen as clearly as at lower magnification, but its position is probably accurate to within 1 inch, which places it within 2/1000 inch of its actual position as seen at 100 magnification. Keeping this in mind, we can proceed as follows.

30. Facts established by continuous micrographs taken from weld through parent metal at a distance of .05 inch below welded face. Magnification is 500 diameters. Thickness of Plates 2W3, 22W3, 24W3 was 1/2 inch, Plate 4W3 was .38 inch thick.

Item 2W3

Maximum dispersion of carbide (directly related to maximum hardness) occurs 4 inches (.008") from the fusion line and continues through 8 inches (.016") This checks with the hardness contour plotted on Plate 6 for the item in the previous report (NRL No. M-1303) showing maximum hardness starting near the fusion line and dropping off after .02 inch. The large grain size gradient in this sample from weld to parent metal may explain why maximum hardness occurs closer to the fusion line than in the other samples, it being known that an increase in grain size retards the start of and/or the rate of the transformation in quenching. The appearance of the zone of maximum dispersion is shown at a magnification of 2000 diameters in Plate 3 and indicates the presence of fine and medium pearlite.

Item 4W3

The presence of nodular pearlite growing from grain boundaries and encroaching on grain core material having an acicular structure is in evidence. The appearance of the fan-shaped pearlite nodules and the acicular structure at high magnification (2000 times) is shown in Plate 3. The acicular core is believed to be due to the split transformation of this material which forced the formation to take place at a lower temperature. The relative hardness of the latter structure and the nodular pearlite is seen from Plate 4 at 500 times magnification for a hardness test made with the Vickers type tester using "no load" and spacing the indents at intervals of .0025 inch. The pictures show several areas where some grains were caught with three or more indents and in every case the core (acicular structure) is harder than the nodular pearlite.

Item 22

The structure here is partially acicular with a tendency toward the Widmanstaetten pattern and it will be noted that grain boundaries are not outlined with ferrite. At 2000 magnification the individual lamellae are seen (Plate 3).

Item 24

This structure is typically martensitic, indicating a low transformation temperature and the grains have thin envelopes of ferrite. Martensite is definitely shown at 2000 magnification for this item in Plate 3. Fissuring took place in the transition zone of this material in the W_3 weld.

31. The series of micrographs shown in Plates 5, 6, 7 supply the evidence of the suitability of the final quench procedure chosen for duplicating the transition zone structure next to the weld bead. The structure of Item 22 for the weld quench test is the only one which is not reproduced and this is ascribed to the longer time required to heat the half-size Charpy samples than is the case for the transition zone of the weld. It is believed that the short time at high temperature in the latter case is not sufficient to put the Vanadium carbides into solution while in the weld quench sample, 1-1/2 minutes heating apparently puts all the carbides in solution, resulting in a harder structure on quenching. The large grains grown in this sample would also indicate the loss of Vanadium carbide by solution in the austenite and thus promoting grain growth.

32. The data on grain size of the transition zone material of the various welded items shown in Table 6 are considered to be of qualitative value due to the arbitrary method used. An accurate method of determining grain size of the transition zone would of necessity require a survey of the entire heat disturbed area and would involve a statistical statement of the frequency with which the large grains occur for several cross sections transverse to the bead. The factors of grain size gradient from the bead into parent metal and around the bead would have to be used for weighting the determination of grain size. The method employed is therefore a relatively rapid one which permits grading the grain size developed into three catagories of fine, medium and coarse, and it is intended in presenting the table that closer comparison than this should not be made. Furthermore, it would be desirable, when time permits, to check the values, obtained by simple polishing and etching methods, with other methods such as the McQuaid Ehn test for grain size (this test is now underway). It appears from the grain size data that vanadium, molybdenum and columbium decrease the grain size, while carbon and nickel increase it; although final confirmation of the conclusions should wait for check tests as suggested above.

33. Table No. 4 giving a comparison of eleven materials tested for impact before and after the weld quench heat treatment is the most important data resulting from the investigation. It suggests that steels of poor weldability by ordinary methods, without preheat or subsequent treatment, may be weeded out on the basis of percentage loss in impact value along with a consideration of absolute impact value after heat treatment. Such steels as Items 3, 22, 24, 28 and 31 show a considerable loss of impact resistance and further work will make possible the setting of a definite limit for this figure. It will be noted that Item 2, which gives no trouble in welding, suffers little loss in impact, while Items 27 and 30 which are commercial steels designed especially for good weldability, suffer no loss in impact. In fact, Item 30 appears the better of the latter two, since an improvement in impact resistance is obtained. For the molybdenum series, Items 17, 18, 19, the lowest molybdenum content of .19% for Item 17 seems to be optimum. The data are therefore seen to make possible establishing degrees of excellence-of-suitability for materials in welding besides indicating where the analysis would require special methods of welding.

Welding Tests

34. The results of welding tests as given in the progressive hardness curves, Plates 9, 10, 12, indicate the same situation as prevailed

for tests reported in the previous report, i.e., maximum hardness in general, occurs a slight distance from the fusion line. Even where the hardness appears to be a maximum at the fusion line due to the first indent in the transition zone being a maximum, it will be noted that the center of the indent had to be at least 1/2 to 1-1/2 diameters of the indent from the line, thus placing maximum hardness for these cases nearer to the fusion line but not necessarily at the line. The mass effect tests are of interest in showing maximum hardness for a mild steel, Item B, to occur at 1-inch thickness while a steel of considerable hardenability, Item 36, does not reach a maximum except beyond 1-3/4 inch thickness. The latter, when welded in thin sections 1/4-inch, develops a low hardenability, but in the region of subcritical anneal at the end of the transition zone, the hardness drops considerably below parent metal hardness. The hardness surveys for the cast steels are parallel to what we would expect for rolled steel of the same composition with the added mass of 1/4-inch greater thickness due to the cast, plates being 3/4-inch thick instead of 1/2-inch as for the rolled steels.

35. The curves of Plate 17 summarizing hardness tests on all rolled steels investigated lead to some interesting conclusions regarding composition. It is seen that Items B, 21, 6, 9, have approximately the same percentage hardenability as Item 4 (corrected for 1/2-inch thickness) and Item 3; the latter two have higher carbon content and lead the others in maximum hardness produced. In addition, Items B, 21, 6, 9, show considerably lower parent metal hardness and an absolute hardness increase of less than 100 units as shown in curve B of the same plate. The curves of Plate 17 are considered as proof of the fallacy of attempting to define weldability of steels solely by means of hardness surveys of the transition zone; for example, if we use a tentative limit of 65% hardenability and in addition a limit of 100 absolute units of hardness, we would exclude Items 22, 4, and Items 10 to 33. We would, however, include Item 3. On the other hand, if we use tentative limits as above and limit loss of impact for the weld quench sample to not more than 30% with an impact value not less than 15 foot pounds for the half-size Charpy sample after heat treatment, there is then no question but that Item 3 which might be expected to give some trouble in welding would be excluded. It may be necessary to raise the above tentative hardenability limits if it is found that items such as 9, 10, 6 and 21, which are excluded on the above basis of hardenability do not suffer a loss of impact value greater than 30%. The curves of Plate 16 comparing impact values for weld quench samples of the molybdenum series, illustrates the information which will be available for the entire series when tests have been completed.

36. It should be noted that for the 3-1/2% nickel series, the curves of Plate 15 indicate a sharp drop in maximum hardness with decrease in carbon, and yet Plate 17 shows these grades so close as to leave little to choose between them on the basis of per cent hardenability. The weld quench impact tests are expected to separate such compositions and permit a determination of degree of suitability for welding.

SUMMARY AND CONCLUSIONS

37. A method of heating and quenching half-size Charpy samples has been developed which gives reproducible results and in which the hardness, grain size and microstructure is of a fair order of agreement with the area of maximum hardness in the transition zone of welded samples. From the data obtained for one composition, Item 22, containing vanadium, it appears possible that compositions having constituents of difficult solubility, capable

of affecting hardness on quenching, will appear in a worse light with the above weld quench method than is actually the case in a weld. It is proposed in the report to investigate more rapid methods of heating in order to perfect the weld quench test.

38. It was shown that the interrupted quench, using two quenching baths at different temperatures, was necessary in order to produce the metallurgical effect of the actual quenching cycle of the weld transition zone. If a single quench were to be used, it would be necessary to change the conditions for each sample tested. The interrupted quench is a compromise with the actual (ideal) quench but produces the desired objective, i.e., separating out the steels of poor weldability and establishing degrees of weldability for the weldable steels on the basis of per cent hardenability, hardness increase, and impact before and after weld-quenching.

39. The weld-quench test is a simple one and can be made for a low cost. It will be necessary to prepare two or three half-size Charpy samples for determination of original impact value before weld-quenching; three half-size Charpy samples can be used to determine the effect of the weld-quench on the impact value. The hardness before and after weld-quenching can be determined from the remainder of the impact test samples. With such a low cost for the test, it should be possible to apply it to materials from different heats of the same composition or different plates of the same heat. In fact, with perfection of the method to apply to any and all compositions, it should be possible to set up the quenching procedure to duplicate conditions for increasing speeds of welding, preheat, and increasing mass at constant speed and an answer to questions of maximum speed of welding, preheat necessary and maximum hardness for a certain cross section could be answered by the results of a simple weld-quench test.

40. The information supplied by the thermal cycle curves for the welded Plates 22W5, 22W6, and 4W3 has been shown to be useful in determining the causes for the wide variety of metallurgical changes occurring throughout the transition zone. It appears desirable to establish the thermal gradient and the variation of thermal cycle with distance from the fusion line for several points in the same sample and this is to be attempted for future tests. The setting up of standards as for paragraph 39 above would require that the corresponding thermal cycles for different welding speeds, preheat temperatures and plate mass be obtained at the start.

41. Additional data of the same nature as reported in the previous NRL report have been obtained for hardenability and hardness increase for a number of additional materials. It has been possible with the new data to show the very rapid increase in hardenability of the 3-1/2% and 2% nickel steels with slight increase in carbon content and it will remain for the impact tests of weld quench samples to show whether this effect is reflected in a corresponding loss of impact. The results so far obtained indicate a high loss of impact value for the weld quench samples of high hardenability and the steels of recognized good weldability have low hardenability and suffer no loss of impact value after the weld quench treatment.

42. A comparison of rolled and cast steels versus carbon content has shown hardenability to run parallel for both steels of similar composition, the higher level of hardness for the cast steels being due to their greater thickness. The two cast compositions of low alloy grade, Items 55

and 56, may be regarded as "horrible examples" of what can be expected in the transition zone of alloy castings with a carbon content on the high side, in comparison with lower carbon cast plates which indicate good weldability.

43. In suggesting tentative limits for hardenability and loss of impact in order to exclude certain compositions of steels, it must be noted that what is intended to be set up in the present report is a division of the compositions into two groups. Those steels on the acceptable side of the dividing line are to be considered as of good weldability by ordinary procedures and those, excluded by the above limits are not to be considered unweldable, but rather that they require special attention in welding. The conditions under which the excluded compositions are weldable will be determined, following which a determination and comparison of the toughness of the transition zone can be made.

44. The weld-quench heat treatment described in the report is considered to be a reliable gauge of the suitability of composition of the steels for welding inasmuch as the treatment is made at such a high temperature as to completely obliterate any previous thermal treatment the material may have had. It should therefore be of great value to the steel mill since the weldability of the heat may be determined from billet or slab samples before rolling to plate, with the consequence that rejection of the material at the welding site would be made remote.

TABLE I

SUMMARY OF HARDNESS TESTS ON WELDS

Welding Conditions

Grade EA, Class 2, 3/16" heavy coated rod, 180-190 amperes, 25-27 volts, speed of 6" per minute.

Hardness Testing Conditions

Vickers type hardness testing machine, 10 kilogram load. Indents .05" from top of plate (welded face), .02" apart in transition zone and .05" apart outside.

Item	Thickness "	Transition Zone Maximum	Transition Zone Minimum	Parent Metal	Weld Metal Maximum	Hardness Increase H_V 10 Units	Hardness Increase Per Cent
[illegible]	1/2	266	200	169	193	97	57.4
4	.38 (.340)	327	220	210	224	(130) 117	(62) 56
[illegible]	1/2	340	206	174	215	171	98
26	1/2	413	233	183	254	230	126
[illegible]	1/2	383	215	195	274	188	96
			Mass Effect Samples				
8	1-1/2	282	180	146	215	136	93
"	1	297	180	146	221	146	100
"	3/4	266	180	146	209	120	82
"	1/2	237	175	146	181	91	64
"	1/4	212	155	146	179	66	45
36	1-3/4	503	270	187	262	316	169
"	1-1/2	493	260	187	287	306	164
"	1	483	225	187	278	296	158
"	3/4	455	200	187	230	268	143
"	1/2	446	200	187	224	259	138
"	1/4	282	180	187	209	95	51

Cast Steels (3/4-inch Thick)

Item		Transition Zone Maximum	Av.	Parent Metal	Av.	Weld Metal Maximum	Av.	H_V 10 Units	Av.	Per Cent	Av.
51	W_3	270	276	153	154	195	202	117	122	76.5	79
	W_4	282		155		209		127		82.0	
52	W_3	215	21[illegible]	130	130	197	197	85	85	65.4	65
	W_4	21[illegible]		130		197		85		65.4	
53	W_3	282	287	148	147	209	208	134	140	90.5	95
	W_4	292		146		206		146		100	
54	W_3	421	425	179	179	224	216	242	246	135	138
	W_4	429		179		207		250		140	
55	W_3	405	401	174	177	215	220	231	220	133	125
	W_4	397		179		224		208		116	
56	W_3	613	620	198	204	266	262	415	416	209	204
	W_4	627		210		258		417		199	

TABLE 2

WELD QUENCH TESTS ON HALF-SIZE CHARPY SAMPLES

Part 1 - Samples heated to 1400°C. in graphite resistance furnace for 1-1/2 minutes and quenched as shown below. A = air cooled, Pb = lead quench, N = NaOH quench, O = oil quench.

Quenching Temperature - 550°C.

Quenching Medium	Time in Quench	Cooled after Quench	Hardness Average HV_{10} Item 2 (221)	Item 22 (312)	Hardness Difference between Item 2 and 22
Pb	30 sec.	A	219	242	23
N	20 sec.	A	215	237	22
N	10 sec.	O 25°C.	217	426	209
Quenching Temperature - 500°C.					
N	20 sec.	A	228	236	8
N	1 min.	A	228	240	24
N	1 min.	O 25°C.	228	270	42
N	2 min.	A	219	237	18
Quenching Temperature - 450°C.					
N	1 min.	A	260	287	27
N	2 min.	A	254	293	39
Quenching Temperature - 400°C.					
N	20 sec.	A	245	287	42
N	1 min.	A	288	337	49
N	3 min.	A	305	347	42

Part 2 and Part 3 - Samples heated to 1350°C. in Hayes, Globar furnace with protective atmosphere.

In Part 2 samples were heated in steel block at furnace temperature for 1-1/2 minutes.

In Part 3 samples heated in furnace (not in steel block) for 1-1/2 minutes.

Part 2 and 3 samples received a double quench.
Quench 1 was NaOH for time and temperature specified below.
Quench 2 was NaOH to which 40 mol per cent of KOH was added, the sample being taken out of Quench 1 and immediately transferred to Quench 2 for time and temperature specified below.

TABLE 2 (Continued)

Item Number	2	3	17	18	19	22	24
Transition zone maximum hardness for W_3 weld	221	266	230	258	287	312	503

Part 2 (Table 2)

Test No. 1 - 1st Quench - 550°C. for 12 sec., 2nd Quench - 185°C. for 30 sec.

Av.hardness, $H_{V_{10}}$ after quenching.	191	243	256	289	333	401	503
Per cent of transition zone hardness attained.	87	93	111	108	116	129	100

Test No. 2 - 1st Quench - 525°C. for 12 sec., 2nd Quench - 250°C. for 30 sec.

Av.hardness, $H_{V_{10}}$ after quenching.	217	240	222	261	308	418	496
Per cent attained.	98	90	97	101	107	134	99

Part 3 (Table 2)

Test No. 3 - 1st Quench - 500°C. for 19 sec., 2nd Quench - 275°C. for 27 sec.

Av.hardness, $H_{V_{10}}$ after quenching.	234	257	218	237	258	379	497
Per cent attained.	106	97	95	92	90	121	99

Test No. 4 - 1st Quench - 550°C. for 16 sec., 2nd Quench - 250°C. for 40 sec.

Av.hardness, $H_{V_{10}}$	213	267	249	368	358	402	483
Per cent attained.	96	100	108	143	125	129	97

Test No. 5 - 1st Quench - 525°C. for 18 sec., 290°C. for 24 sec.

Av.hardness, $H_{V_{10}}$	231	259	216		282	366	479
Per cent attained.	105	97	94		98	117	95

Test No. 6 - 1st Quench - 500°C. for 22 sec., 275°C. for 45 sec.

Av.hardness, $H_{V_{10}}$	239	267	236		270	366	455
Per cent attained.	108	100	103		94	117	90

TABLE 3

WELD QUENCH TESTS FOR REPRODUCIBILITY OF RESULTS

Heat treatment of half-size Charpy samples was 1-1/2 minutes at 1350°-1360°C. (without use of steel block for heating), first quench made at 530°C. for 18 seconds, second quench at 310°C. for 24 seconds. Samples were then ground down 5/1000 inch all over and prepared with Charpy keyhole notch. Hardness tests were made on cross section after impact test; the average value for three indents is given below.

Item	Foot Pounds Impact Value Sample 1	2	3	Ft.lbs. Av.Impact for Three Samples	Hardness HV_{10} Av.for 3 indents Sample 1	2	3	Av.Hard-ness for 3 Samples	Per Cent of Transition Zone Hardness Attained Sample 1	2	3	Average for 3 Samples
2	13	16	17	15	217	228	228	224	98	103	103	101
3	17-1/2	12	9	13	255	260	267	260	96	98	100	98
17	24	30(L)	31	28	229	218	217	221	100	95	95	97
18	23	26	25-1/2	25	245	247	245	246	97	97	97	97
19	19	19-1/2	21-1/2	20	265	271	267	267	93	95	93	94
22	8	7	7-1/2	7-1/2	390	372	368	377	125	119	118	120
24	2	2	2-1/2	2	441	450	461	450	88	89	92	89
27	30-1/2	33-1/2	27	30	210	205	200	205	108	105	102	105
28	3	3	2-1/2	3	387	400	426	404	96	99	105	100
30	31-1/2	30-1/2	28-1/2	30	235	235	241	237	93	93	95	94
31	5	6	6-1/2	6	383	365	370	372	97	92	93	94

Note 1 - (L) above and in Table No. 4 indicates a sample which opened up at a lamination.

Note 2 - All impact samples were prepared with the 2" length in the direction of rolling and the notch is therefore transverse to rolling direction.

TABLE 4

COMPARISON OF LOSS OF IMPACT VALUE DUE TO "WELD QUENCH" HEAT TREATMENT

Item	Impact Value of "as received" material for half-size Charpy samples — Sample 1	Sample 2	Average of two Samples	Average Impact of Heat Treated Samples (Table No. 3)	Per Cent of Original Impact after Heat Treatment
2	16	16	16	15	94
3	20(L)	18-1/2	19	13	68
17	26(L)	23	25	28	112
18	24	24-1/2	24	25	104
19	24-1/2	25	25	20	80
22	11	13-1/2	13	7-1/2	58
24	20	18-1/2	19	2	11
27	30	29	30	30	100
28	17-1/2	17-1/2	18	3	17
30	23-1/2	25	24	30	125
31	19	18-1/2	19	6	32

TABLE 6

GRAIN SIZE OF W_3 WELDS

The transition zone around the fusion line was searched for large grains at a magnification of 100 to 200, as required. The twelve largest grains were then averaged to obtain the figure of average, maximum grain size at 100 magnification.

Item	Grain/sq.in. at 100 x	
34	10	Fine
22	10	
19	6.3	
33, 18	5.6	
23, 17	4.3	
29	2.7	Medium
13, 14, 27	2.2	
15, 30, 11	1.9	
6, 5	1.8 - 1.7	
32, 1	1.6	
20, 31, 2	1.5	
9, 21, 10	1.4 - 1.2	
28	.98	Coarse
24	.70	
35	.46	
25	.45	
26	.43	
3	.20	
4	.13	

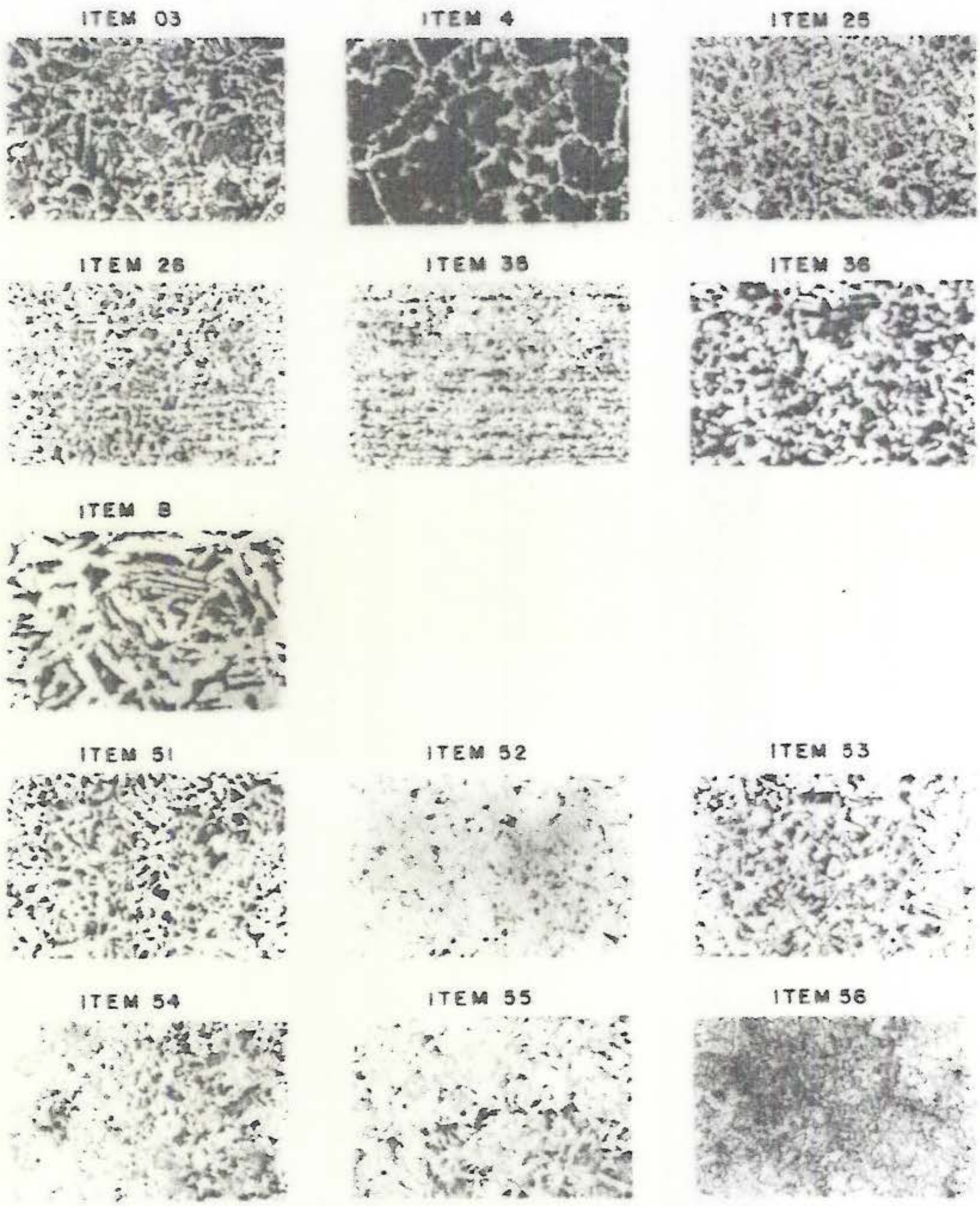
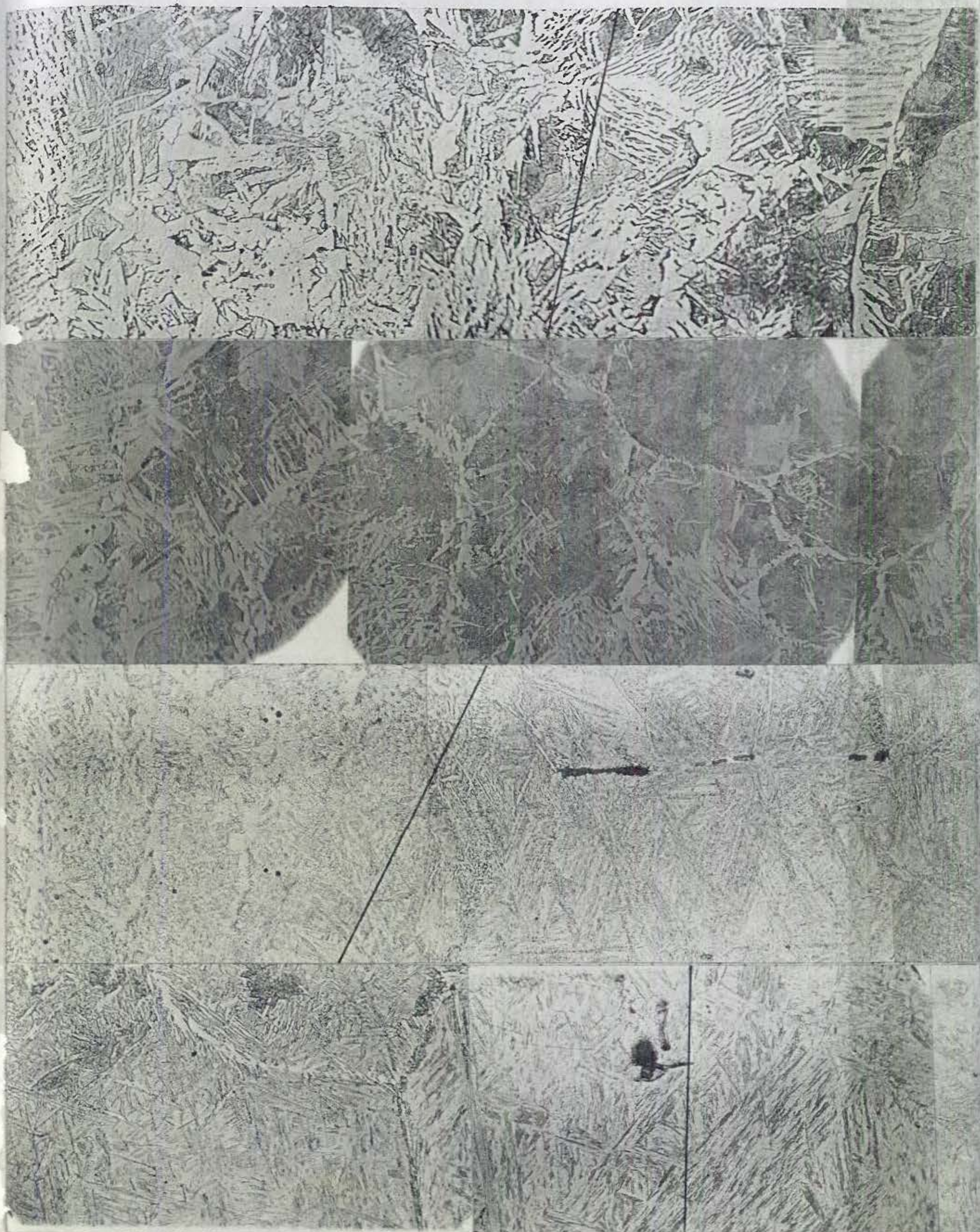

ITEM 03
ITEM 4
ITEM 25
ITEM 26
ITEM 35
ITEM 36
ITEM 8
ITEM 51
ITEM 52
ITEM 53
ITEM 54
ITEM 55
ITEM 56

PLATE 1



1382 p1 plate 2

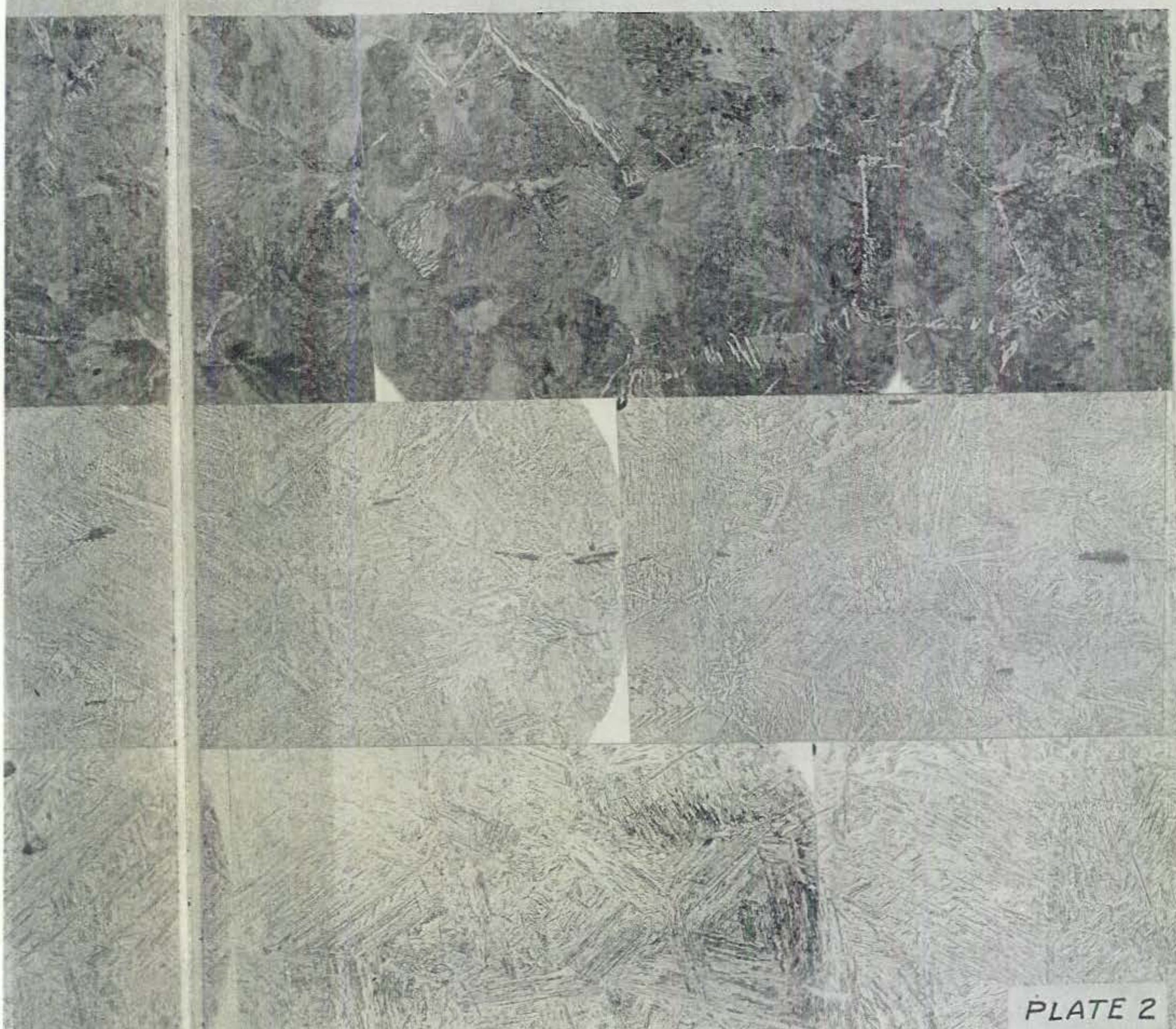
1382 p2 plate2

1382 p3 plate 2

ITEM 2W3

1382 p4 plate 2

ITEM 2W3



ITEM 4W3

ITEM 22W3

ITEM 24W3

PLATE 2

p5 plate 2

1382

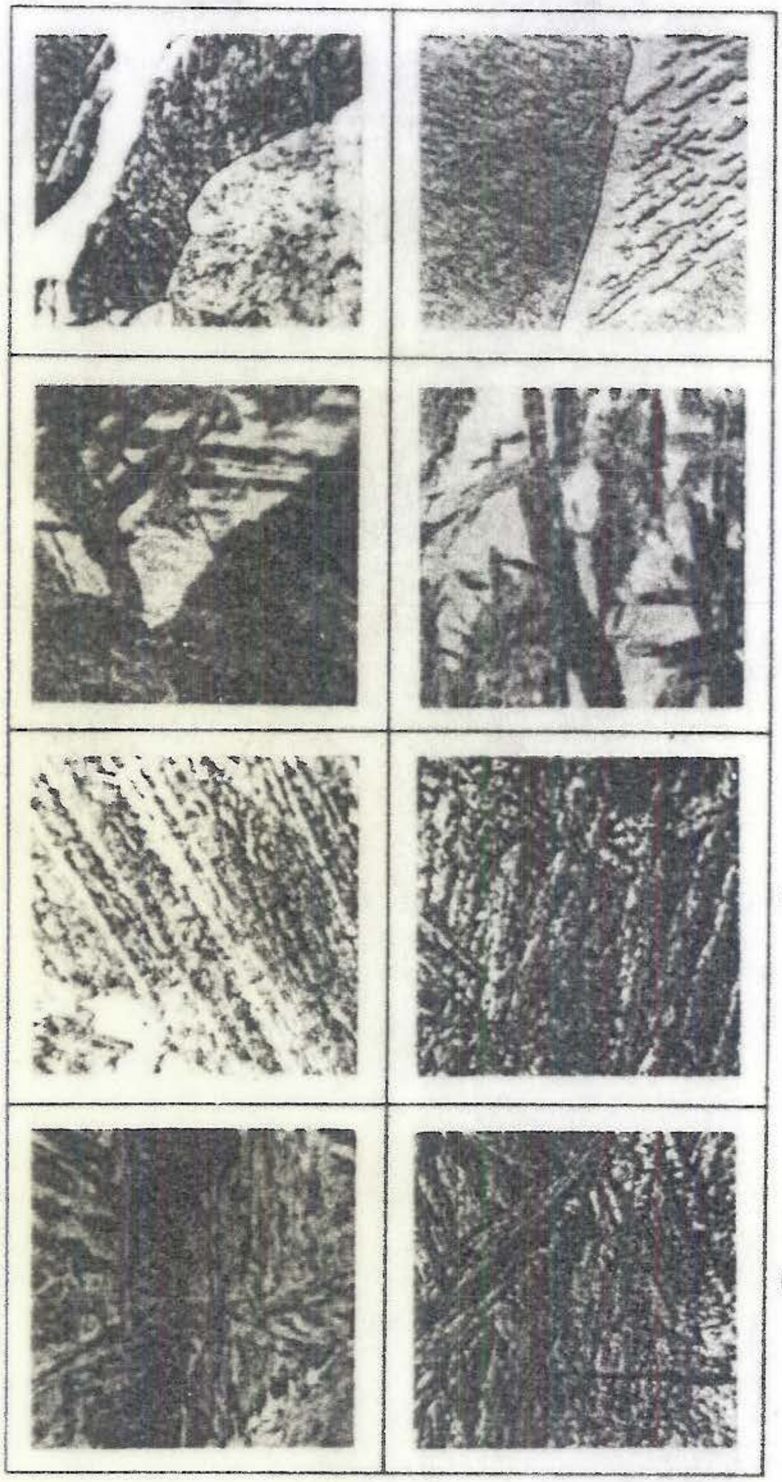
ITEM 4W3

ITEM 22W3

ITEM 24W3

PLATE 2

MAGNIFICATION—2000 TIMES



ITEM 2W3

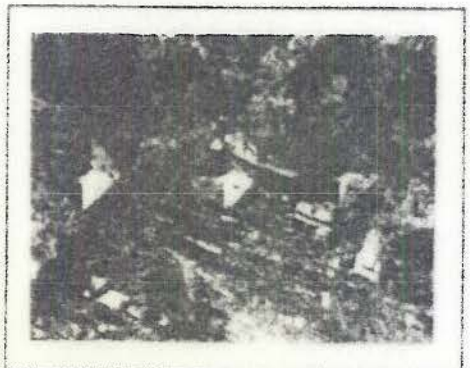
ITEM 4W3

ITEM 22W3

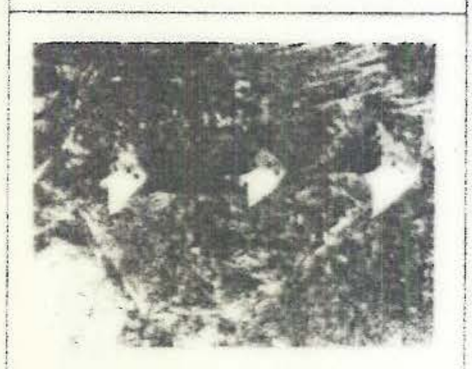
ITEM 24W3

PLATE 3

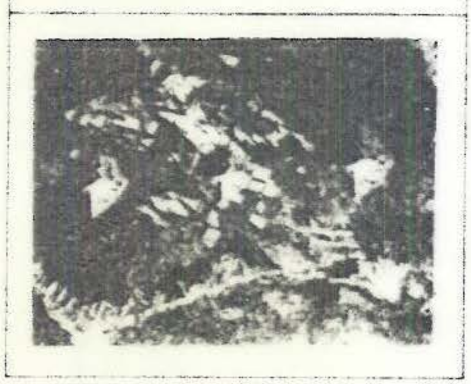
MAGNIFICATION — 500 TIMES



ITEM 4W3



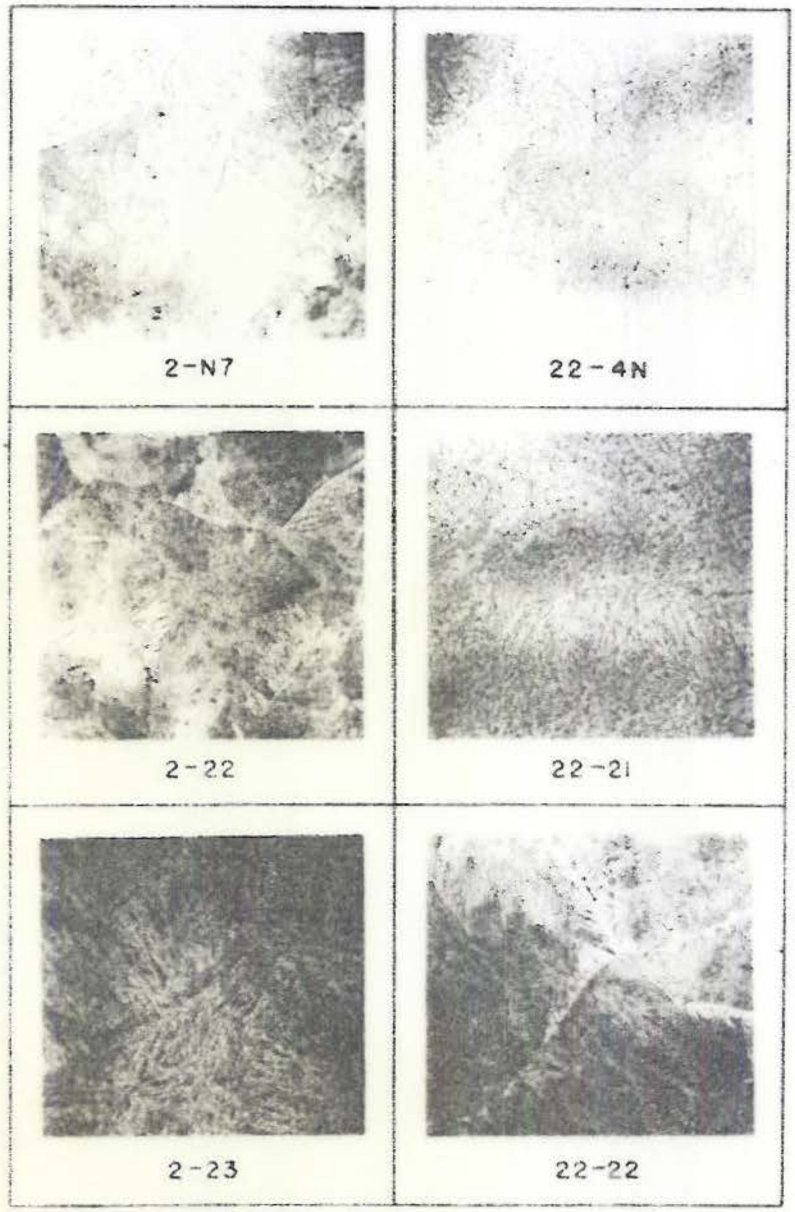
ITEM 4W3



ITEM 4W3

PLATE 4

MAGNIFICATION — 250 TIMES



ITEM 2 ITEM 22

PLATE 5

MAGNIFICATION — 250 TIMES

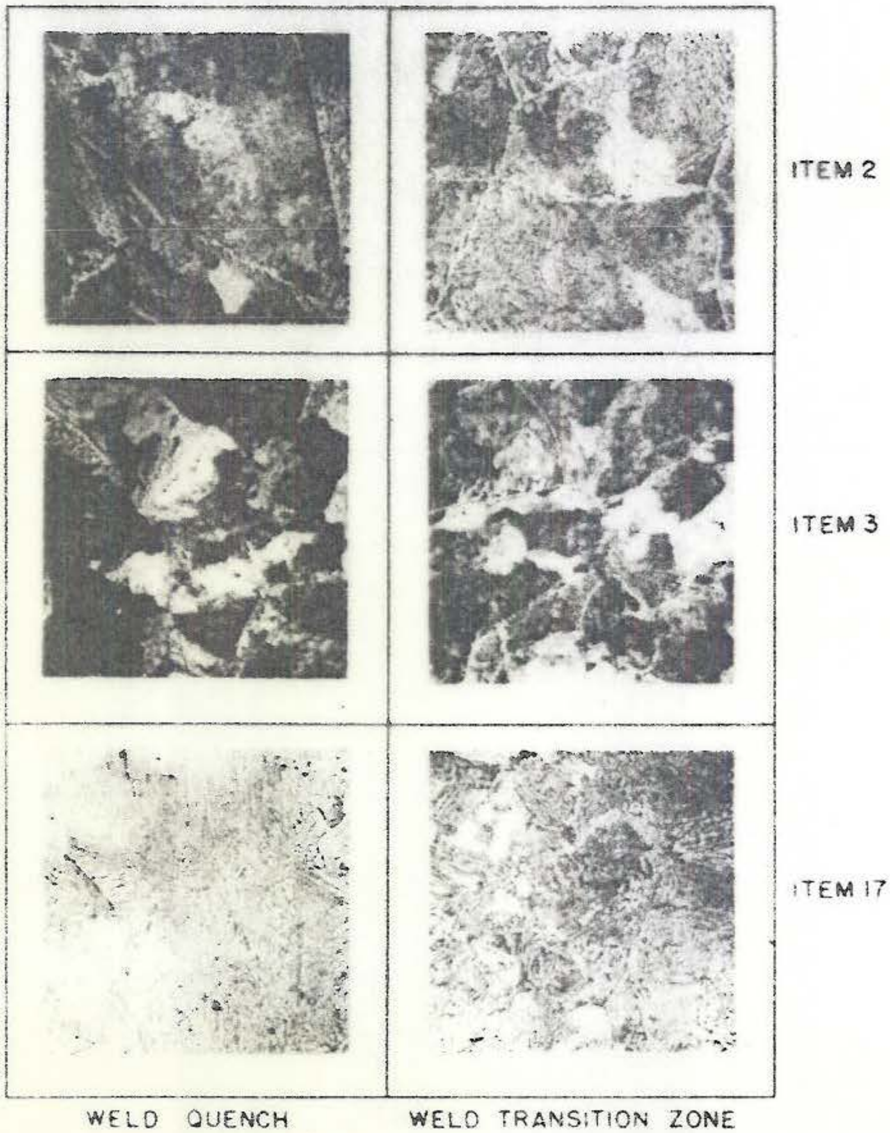
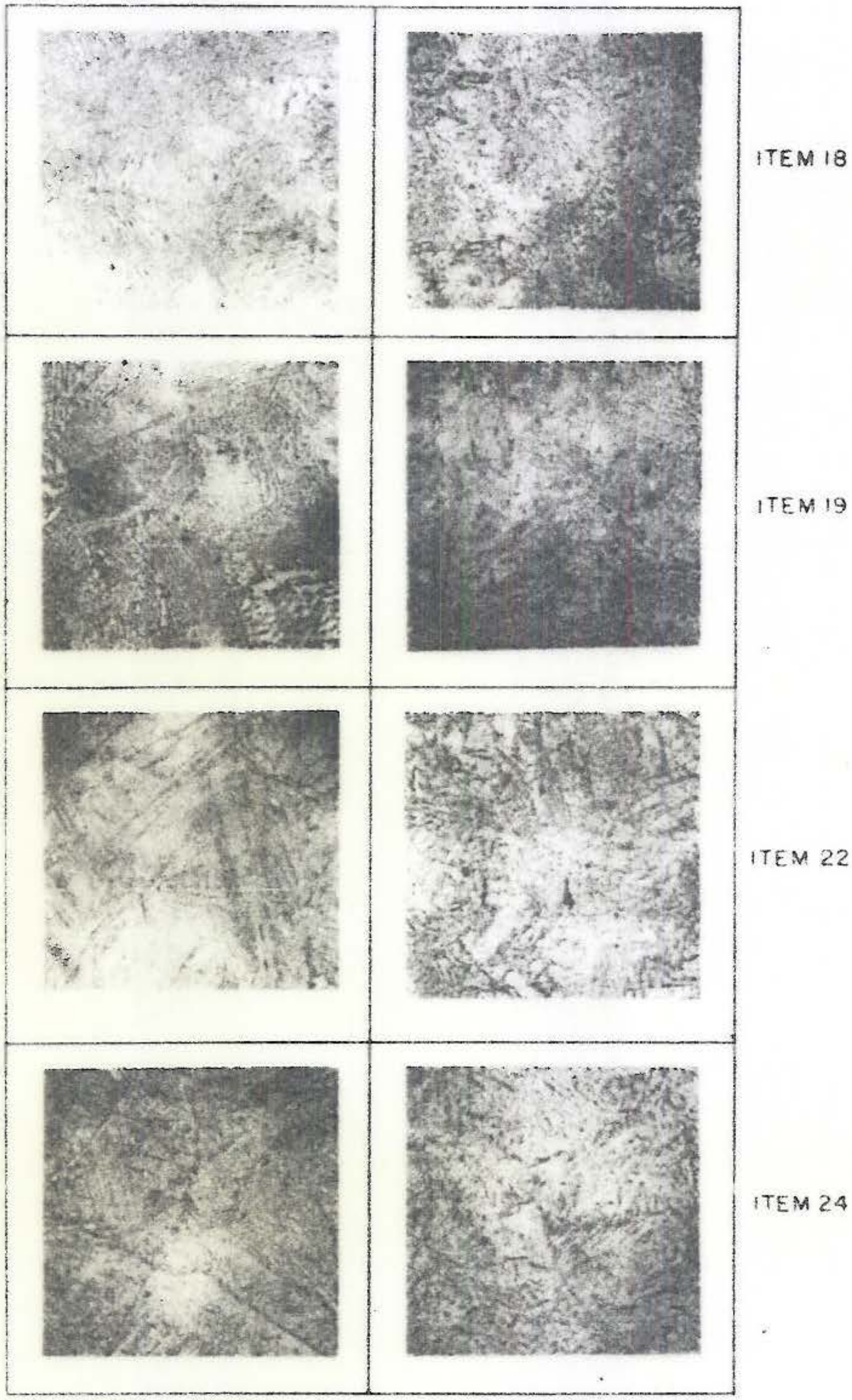


PLATE 6

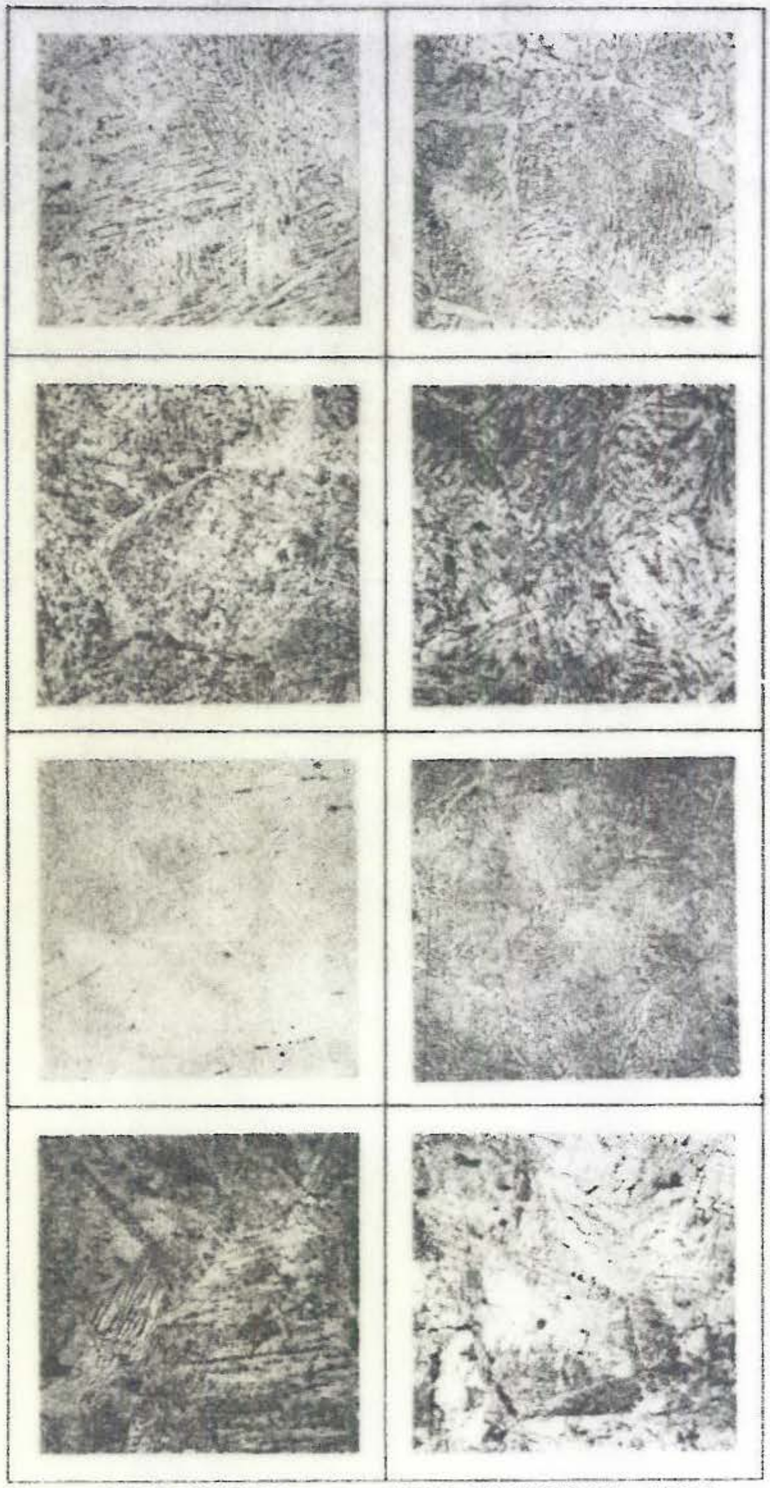
MAGNIFICATION — 250 TIMES



WELD QUENCH　　WELD TRANSITION ZONE

PLATE 6A

MAGNIFICATION — 250 TIMES



ITEM 27

ITEM 28

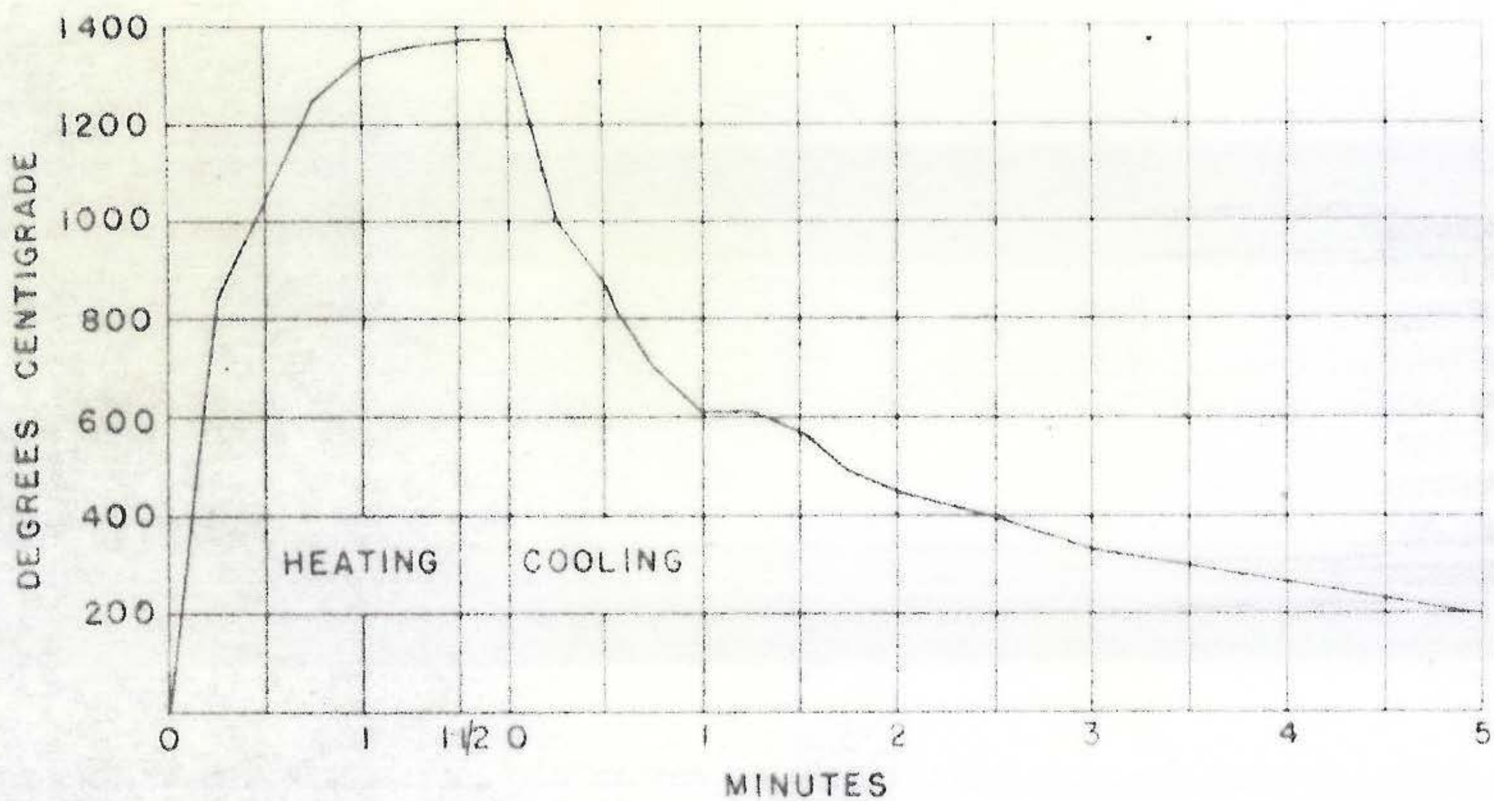
ITEM 30

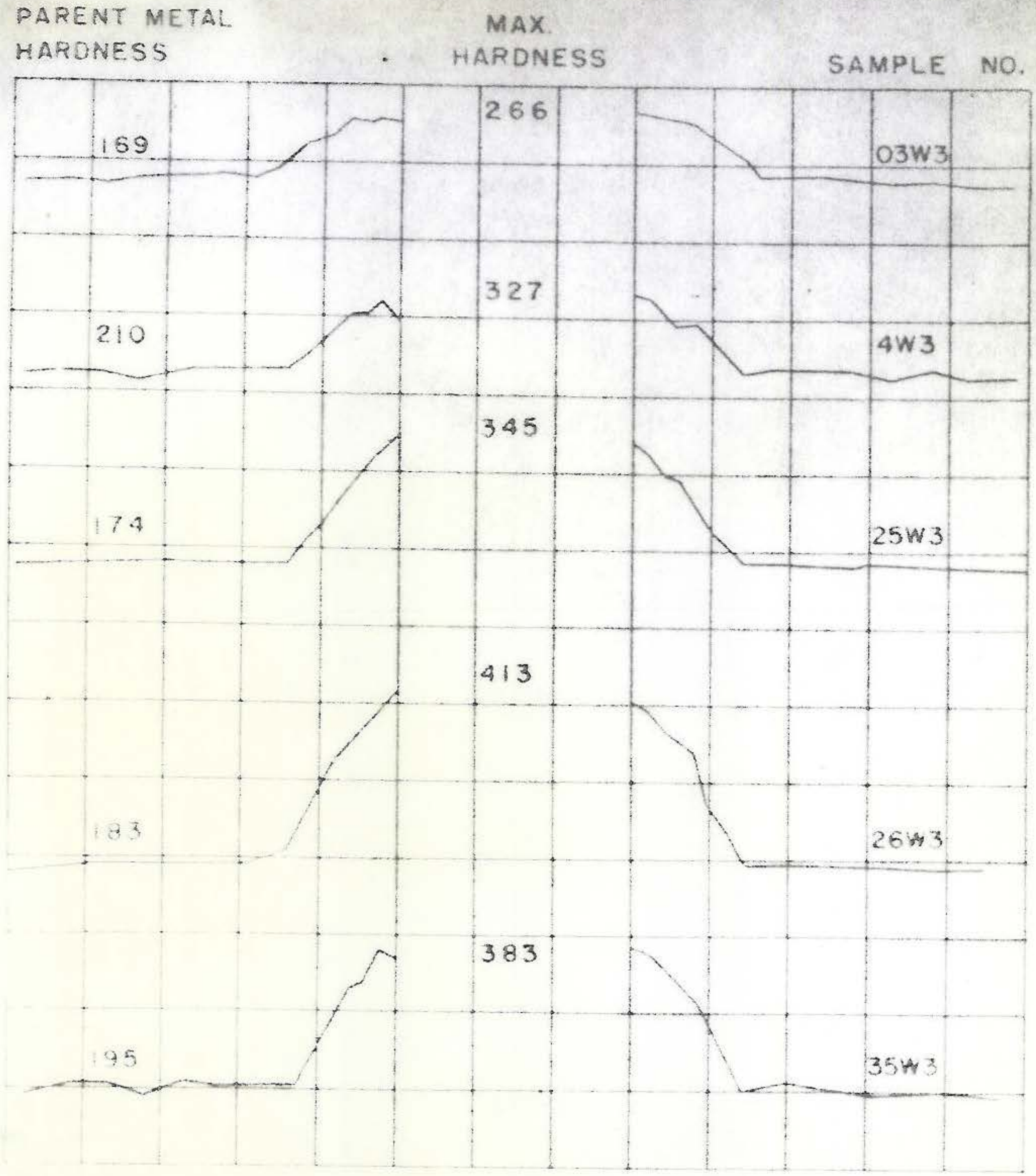
ITEM 31

WELD QUENCH — WELD TRANSITION ZONE

PLATE 7

THERMAL CYCLE FOR ".197 X ".394 X 2" O SAMPLE, ITEM 2, HEATED IN IRON BLOCK AT 1366° C. AND COOLED IN STILL AIR.




PARENT METAL HARDNESS
MAX. HARDNESS
SAMPLE NO.
266
169
03W3
327
210
4W3
345
174
25W3
413
183
26W3
383
195
35W3

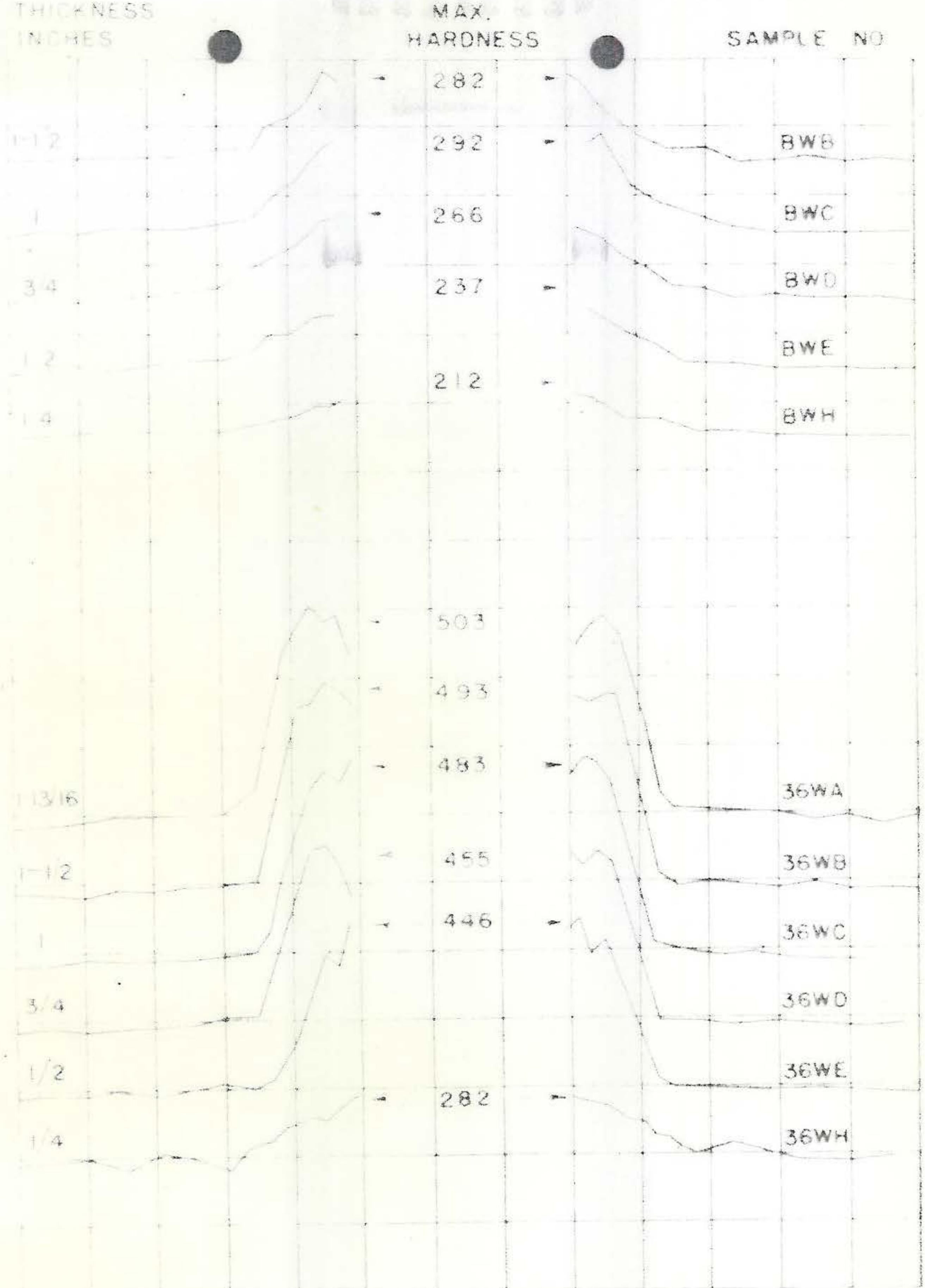
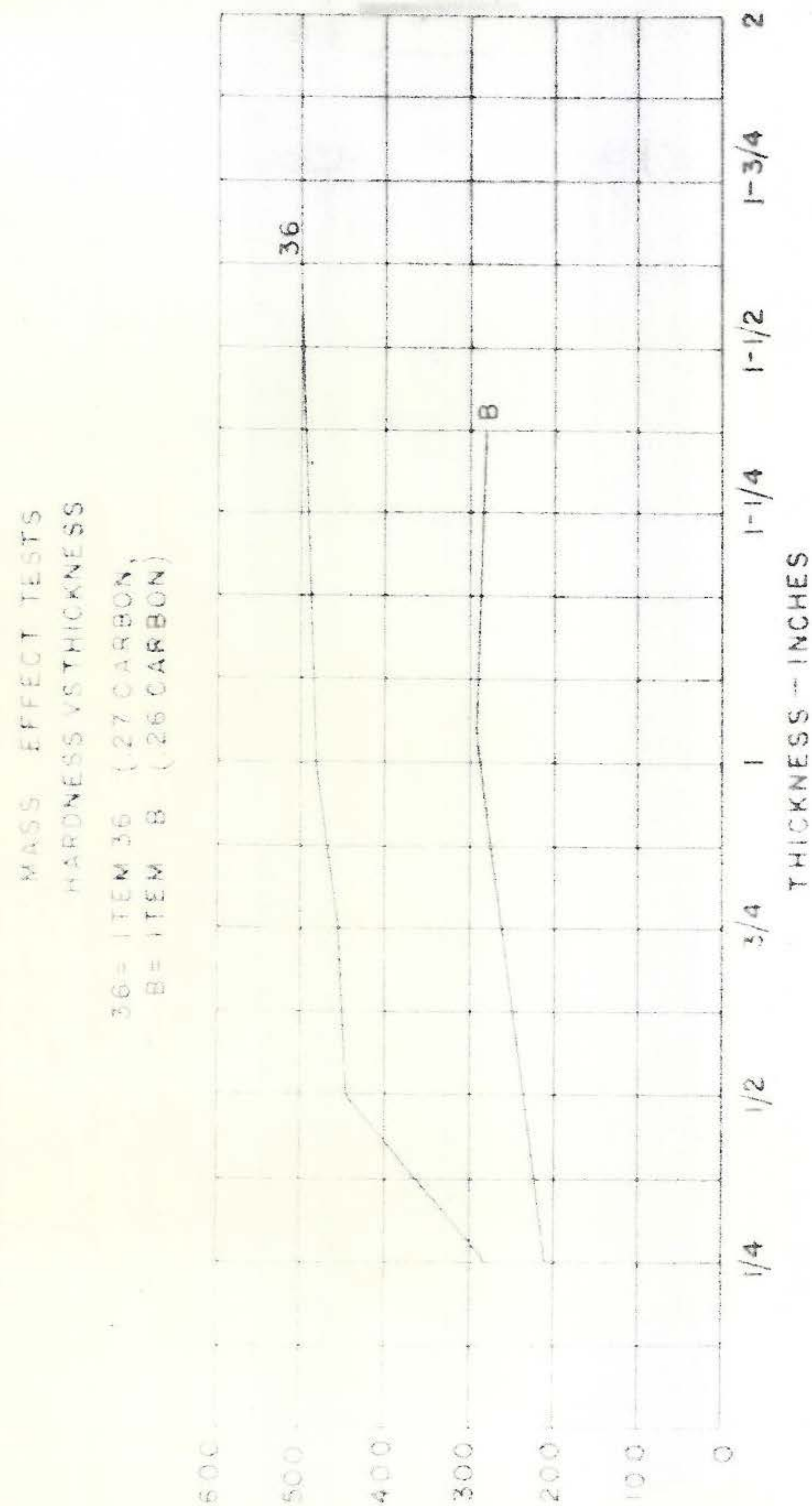
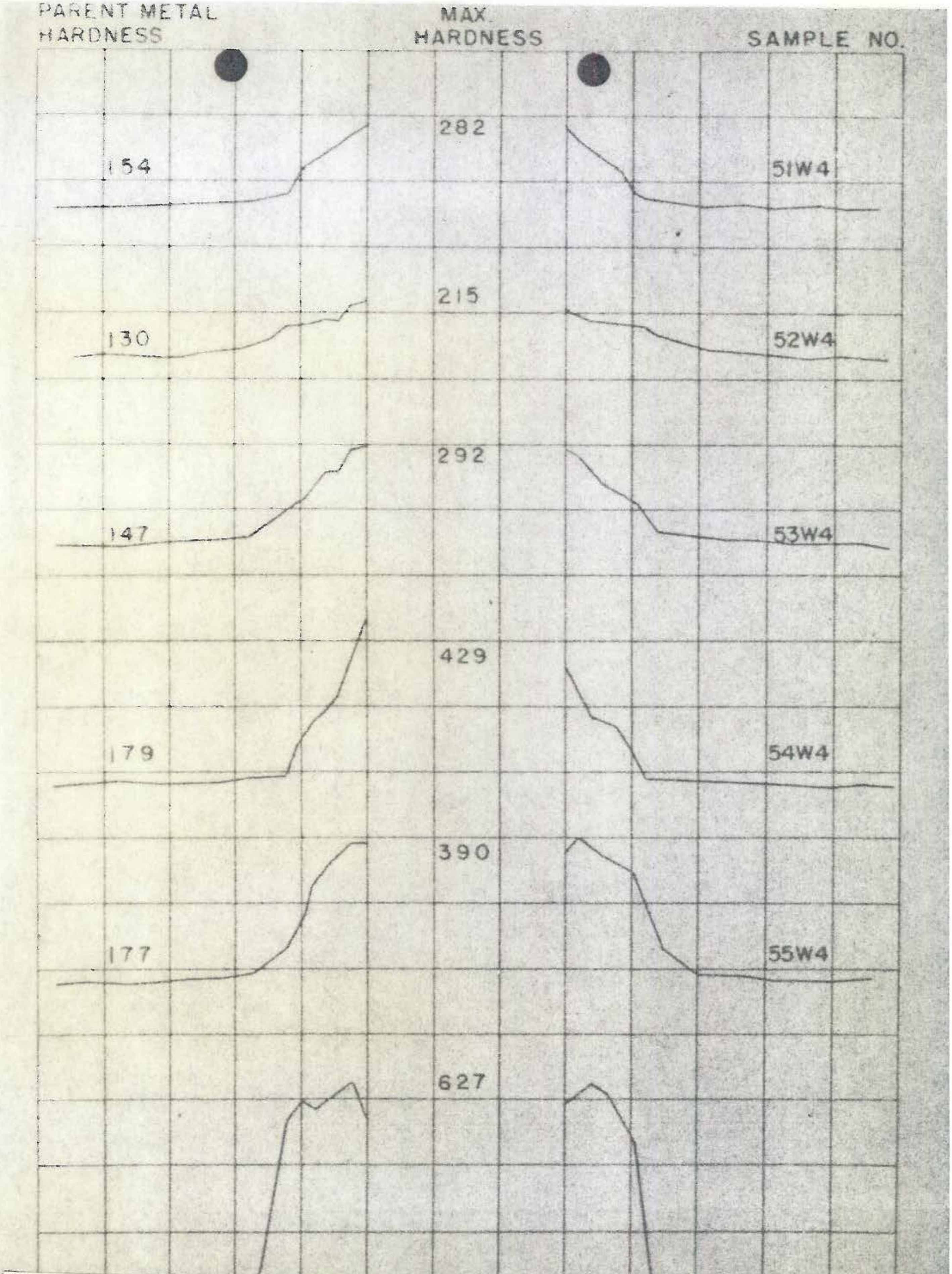
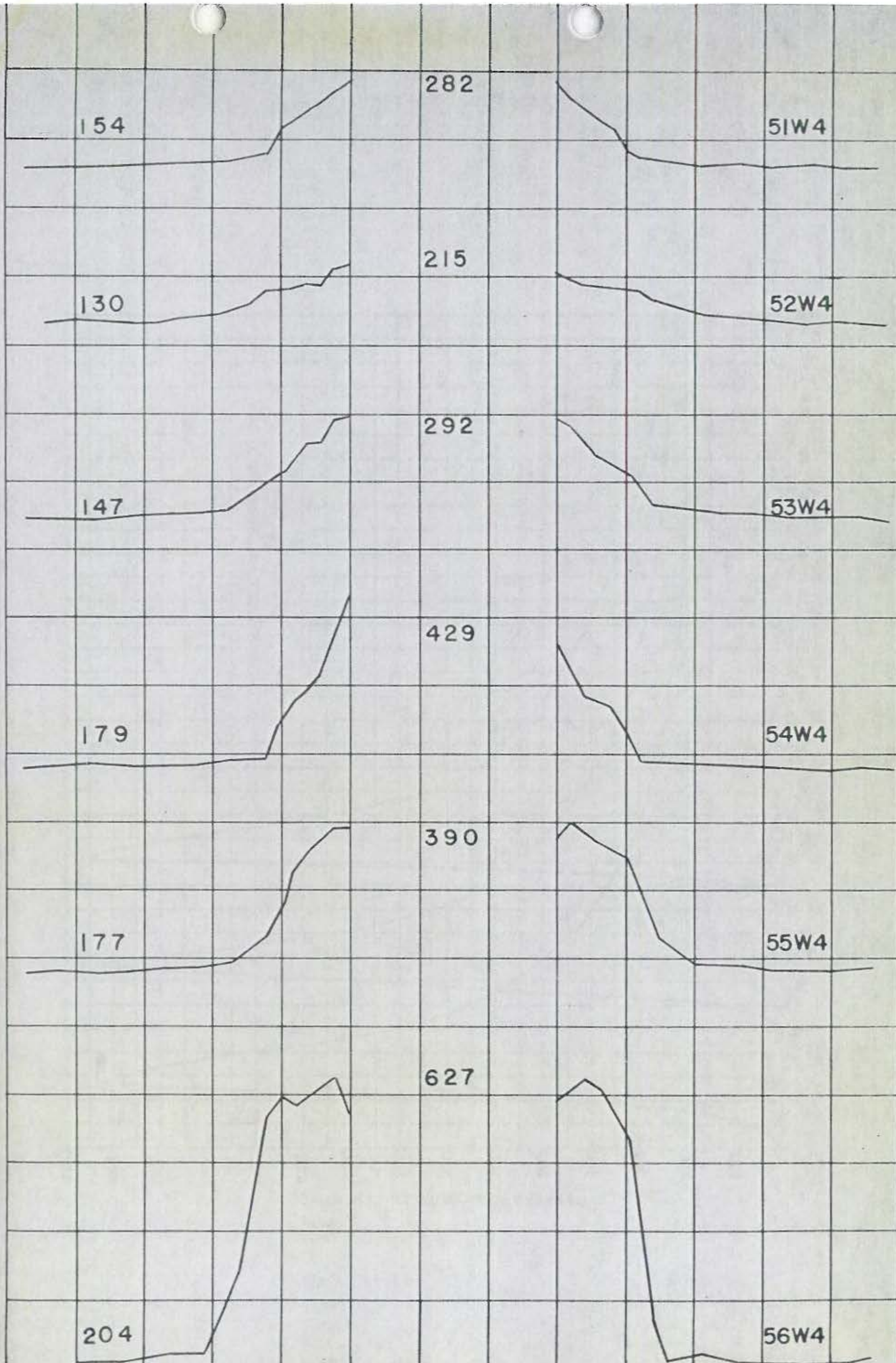

THICKNESS INCHES
MAX. HARDNESS
SAMPLE NO
1-1/2
1
3/4
1/2
1/4
282
292
266
237
212
8WB
8WC
8WD
8WE
8WH
1-13/16
1-1/2
1
3/4
1/2
1/4
503
493
483
455
446
282
36WA
36WB
36WC
36WD
36WE
36WH

PLATE 10


MASS EFFECT TESTS
HARDNESS VS THICKNESS
36 = ITEM 36 (.27 CARBON)
B = ITEM B (.26 CARBON)
36
B
HARDNESS - HV10
600
500
400
300
200
100
0
THICKNESS - INCHES
1/4
1/2
3/4
1
1-1/4
1-1/2
1-3/4
2


PARENT METAL HARDNESS
MAX. HARDNESS
SAMPLE NO.
282
154
51W4
215
130
52W4
292
147
53W4
429
179
54W4
390
177
55W4
627



1382

PLATE 12

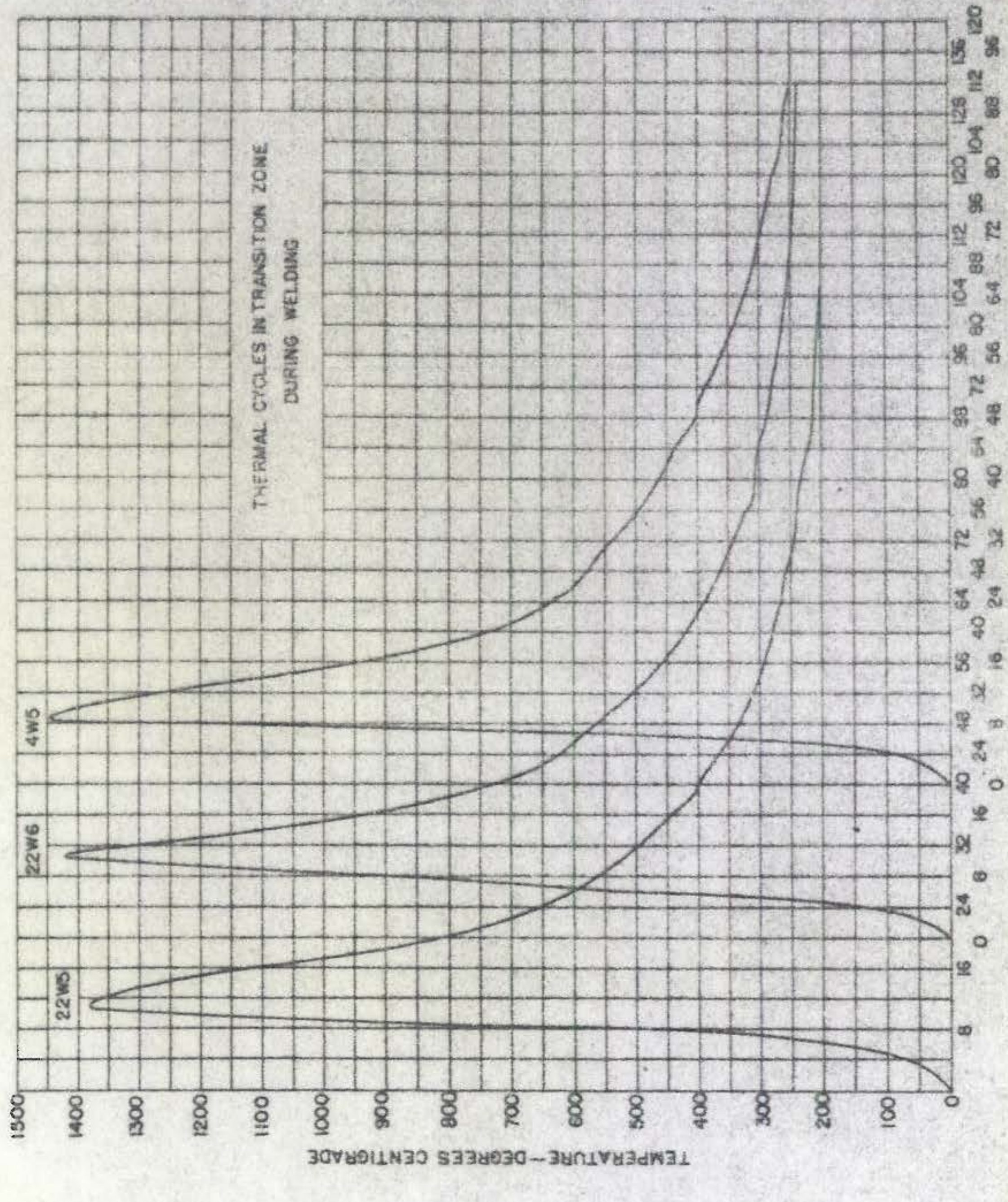
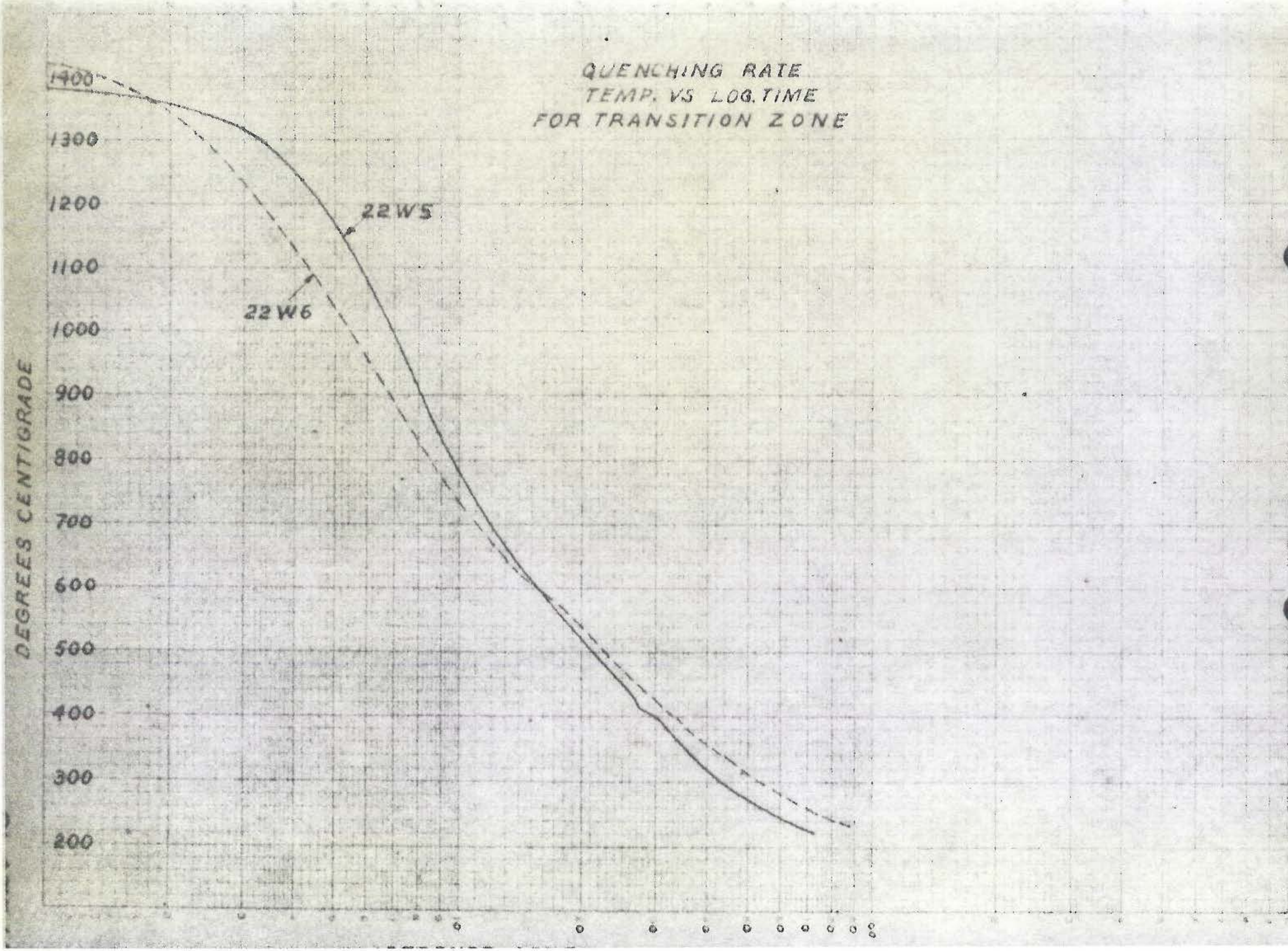
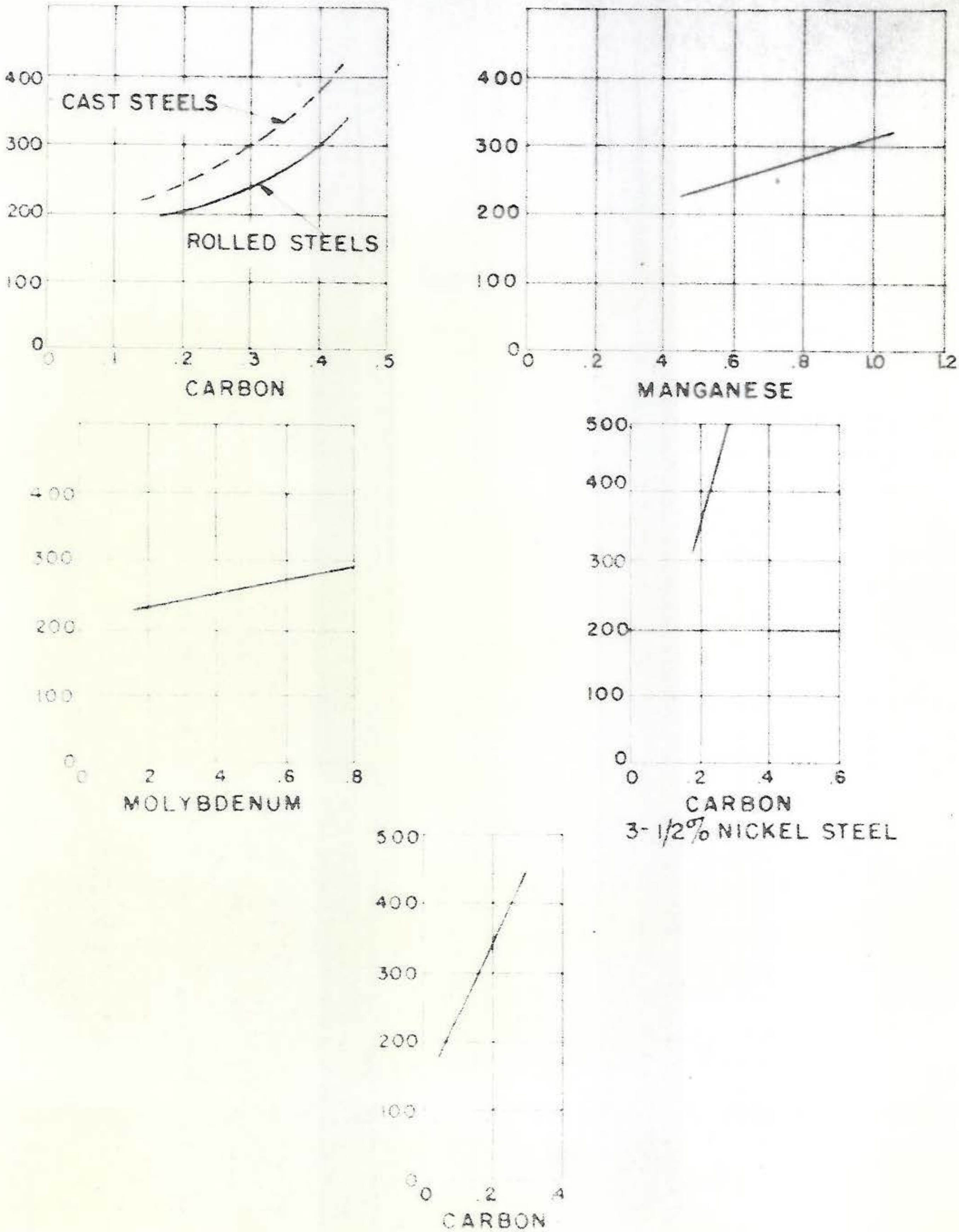

THERMAL CYCLES IN TRANSITION ZONE
DURING WELDING
22W5
22W6
4W5
SECONDS
TEMPERATURE—DEGREES CENTIGRADE

PLATE 13


QUENCHING RATE
TEMP. VS LOG. TIME
FOR TRANSITION ZONE
22W5
22W6
DEGREES CENTIGRADE
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200

MAXIMUM HARDNESS VS COMPOSITION FOR TRANSITION ZONE



2% NICKEL STEEL

PLATE 15

IMPACT VS MOLYBDENUM

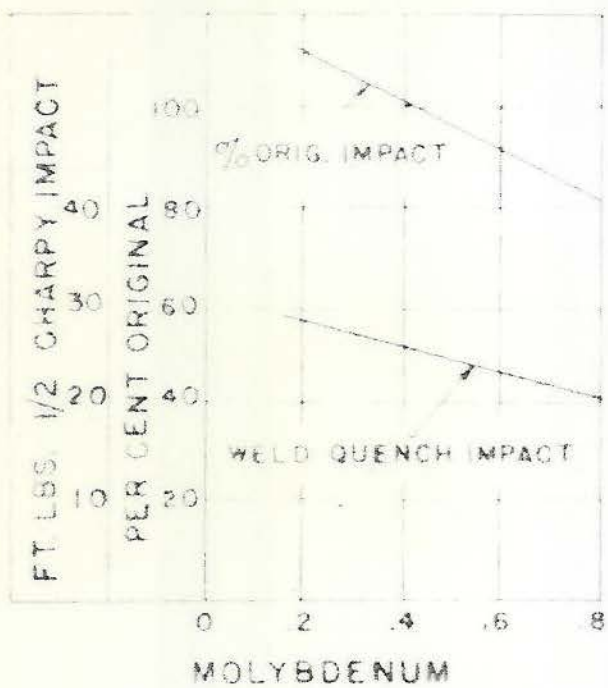
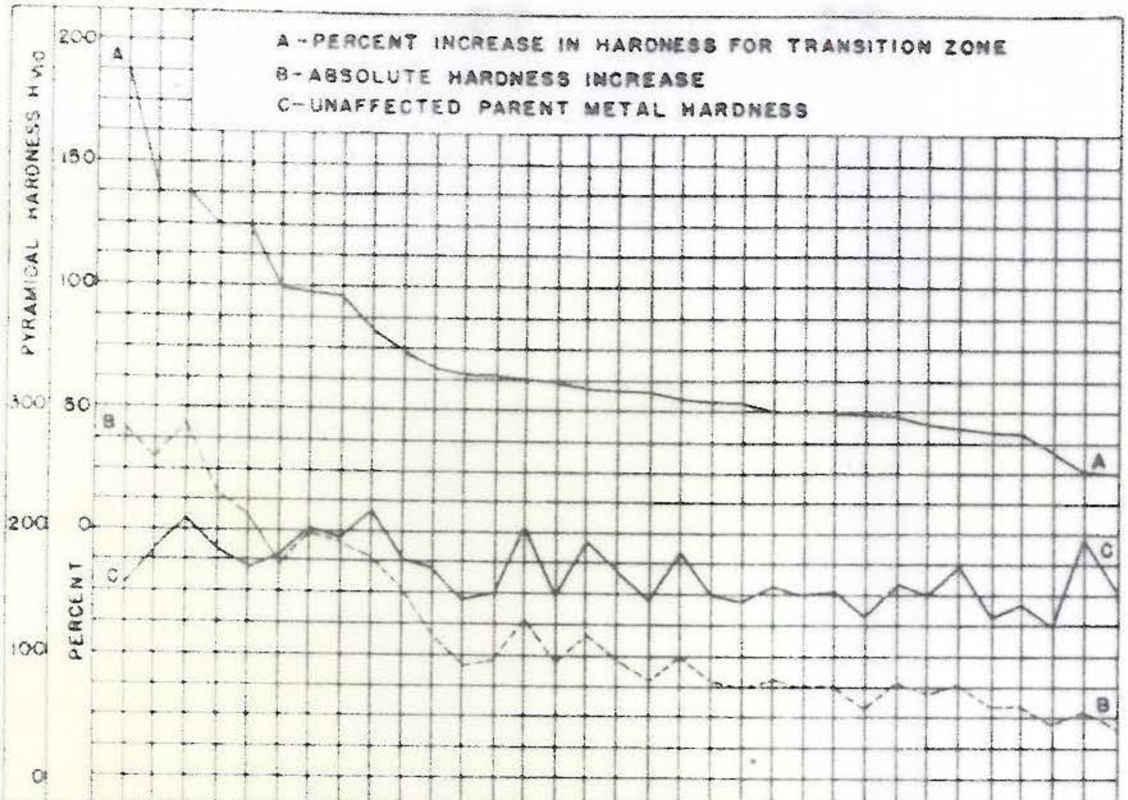


PLATE 16



ITEM	33	36	24	26	34	25	28	35	31	11	10	8	21	4	6	22	3	9	19	13	20	14	15	17	2	23	32	18	1	5	29	30	27
C	.11	.27	.28	.23	.065	.19	.21	.27	.24	.29	.27	.26	.25	.44	.27	.18	.35	.24	.20	.26	.24	.28	.25	.22	.25	.13	.12	.22	.17	.21	.088	.09	.06
Mn	–	.69	.56	.48	–	.40	.70	.69	.74	1.06	.74	.44	.43	.65	.47	1.40	.68	.48	.50	.46	.46	.54	.43	.52	.43	.44	.75	.47	.41	.38	.19	.72	.35
Si	.19	.21	.27	.19	.22	.18	.27	.20	.012	.25	.21	.20	.19	.24	.002	.21	.23	.23	.17	.009	.001	.058	.20	.20	.20	.20	.48	.18	.17	.005	—	.047	.002
Ni		2.38	3.37	3.55		3.63	1.97	2.31	.76																						2.08	.96	1.55
Cu							1.08		1.48																	.75						1.34	.94
Mo	.51				.51				.16										.79					.19		.17		.50				.11	
V																.12																	
Cb					5.51																												
Cr	3.35				5.64																						.34						

NOTE: DASH (—) ABOVE INDICATES PRESENCE OF ELEMENT BUT NO ANALYSIS

PLATE 17

INDEX OF PHOTOMICROGRAPHS

Plate 1 - As received rolled steels, Items 3, 4, 25, 26, 35, 36, B used for welding tests; 100X magnification.
As received, heat treated cast steels, Items 51, 52, 53, 54, 55, 56; 100X magnification.

Plate 2 - Continuous micrograph from weld through transition zone of welds made with 3/16-inch, heavy-coated, grade EA, Class 2 electrode, 180-190 amperes, 25-27 volts at 6 inches a minute. Items 2, 22, 24 were 1/2-inch thick plates, Item 4 was 0.38 inches thick. Micrograph is taken .05 inches below welded face of plate at a magnification of 500X.

Plate 3 - Selected areas of maximum hardness zone of continuous micrographs in Plate 2 shown at a magnification of 2000X for Items 2W3, 4W3, 22W3, 24W3.

Plate 4 - Pyramidal hardness indents made at intervals of .0025 inches at "no load" in Item 4W3 transition zone. The middle indent in the three pictures is approximately .015, .025, .04 inches from the fusion line, respectively. Magnification is 500X.

Plate 5 - All micrographs on this plate are at 250X magnification with the following schedule; the first number before the hyphen giving the number of the item.

	Heat Treatment	Quench			Cooled after
Sample No.	1400°C.	Bath	Temp.	Time	Quench
2-7-N 22-4-N	1-1/2 min.	Lead	550°C.	30 sec.	Air
2-22 22-21	1-1/2 min.	NaOH	550°C.	20 sec.	Air
2-23 22-22	1-1/2 min.	NaOH	550°C.	10 sec.	Oil

Refer to Table 2, Part 1, for hardness values.
Note:- Due to improper mounting, the pictures of 2-23 and 22-22 samples have been put into the reverse positions on Plate 5.

Plate 6 - All micrographs on the left side of the plate show the
6A structure of the corresponding item after the weld quench treatment and on the right is given the structure of the transition zone for a W3 weld of the same item, both being at a magnification of 250X. For hardness values refer to test No. 5, Table No. 2, which also gives the heat treatment.

Plate 7 - This is the same as Plate 6 above except that reference should be made to Table No. 3 and No. 4 for hardness and impact values. The magnification is 250X.

THE THERMAL STUDY OF WELDING (Étude Thermique des Sondures).

A. Portevin and D. Sefèrian. Chaleur et Industrie, Vol. 16, No. 185, Sept. 1935, pages 409-424.

Translated by Walter H. Bruckner, Physical Metallurgist (contract employee).,
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DISCUSSION OF TRANSLATED PAPER

This paper by Portevin and Seferian appears to present the best data so far offered on the heat effect in welding. The experimental work is the important part of this paper, in the writer's opinion, since the mathematics is only an approximation of the heat effect due to the author's having discarded so many terms of the differential expression in order to obtain solutions.

The experimental data, however, are also of an incomplete nature, especially for the arc welds, since the thermocouples did not measure maximum temperatures of the transition zone. This can be noted from curves of Figures 9, 10, 11, 12, 20 where it is seen that the nearest the couples came to the weld line was about 10 mm. (.394 inches). Consequently the temperatures in the arc weld transition zone had to be extrapolated between approximately 500°-750°C. and 1450°C. The exact conditions of welding speed and energy are not specified for each curve, making it difficult to obtain quantitative values from the curves given. However, if we use the criterion suggested by W.G. Theisinger in his Watertown Arsenal Report 642.4/1, we can take the figures for current and voltage given by Portevin and Seferian, e.g., .4 mm. rod used with 115 amps. and 18 volts, 3.3 mm. rod used with 90 amps. and 19 volts. Assuming a manual welding speed of 4-5 inches per minute, we obtain 23,000 to 29,000 Joules/inch as compared with approximately 48,100 Joules/inch used for the welding tests reported in the present 3rd partial report on weldability.

From Fig. 20 of the translation using curve (c) for the 10 mm. (.394) thick plate, we find the authors give a maximum cooling rate of 525°C./sec. from 1420°C. as compared with the maximum rate of 108°C./sec. from 1420° as for the present N.R.L. partial report. This is about 5 times greater than our value, while the energy input is about half and further the lesser thickness of their plate widens the discrepancy still more. However, the plate used for their tests was apparently about 20 inches square which may account for their higher maximum values, together with the fact that theirs are derived and not actual values.

It will be noted that Fig. 20 shows a linear relationship to exist for curve (c) from about 500°C. upward. If we applied this linear relationship to the two points obtained in our data for $22W_5$ and $22W_6$, 1420°C.-108°C./sec. 1380°C.-89°C./sec. the rate would be 0°C./sec. at 1170°C. if the shape were constant for the range. Obviously, the conditions of the thermal cycle for the welding tests carried out at the Naval Research Laboratory do not check with those reported by Portevin and Seferian and it is believed that the discrepancy is due to the extrapolation and derivations carried out by the authors for the high temperature values of maximum cooling rate.

EDITOR'S NOTE (from the original publication).

We publish here a very fine study by Prof. Portevin and Mr. Seferian, two lecturers at the Ecole Superieure de Soudure autogene who are well known in this country for their lectures.

The remarkable work which they have made available treats of an important problem, namely, the determination of the thermal state resulting from an autogenous welding operation and its effect on the finished structure obtained.

We know, in effect, how this thermal state can affect the mechanical properties of the metal and how it can affect the assembly, that is, the allotropic transformations, internal stresses and cracks due to the temperature gradient. In particular the thermal state at each point, as a function of the temperature cycle passing through the point, can produce the effects of tempering (quenching), refining, recrystallization, overheating of which neither the causes nor the processes are susceptible of analytical determination. It is, therefore, necessary to do research on the various factors experimentally and the investigations which are given in this order were made the subject of a communication by Messrs. Portevin and Seferian to the Academy of Sciences, and presented by Henri LeChatelier.

The results of the investigation are presented here. In the first part of their publication the authors analyze the phenomenon of thermal distribution in chosen cases, then they bring to the theoretical research the sanction of an experimental study intelligently conceived and skillfully conducted.

One cannot read the paper without a feeling of real pleasure; it is a genuinely excellent piece of work.

The theoretical determination of the phenomena by mathematical analysis then the application of experimental criteria to their labor of spiritual penetration was done with an elegance and scientific rigor which has something akin to the spirit of the infinite in it.

THE THERMAL STUDY OF WELDING

The temperature distribution in a heated piece has considerable importance on the one hand because of the resulting structure and on the other because of the local mechanical properties, and because of the usual effects on the assembly (deformation, internal strains, fissures).

The mechanical properties are therefore affected doubly in the assembly.

The knowledge of two factors, maximum temperature attained, θ max., and maximum quenching rate V_m permits by means of the "characteristic quenching curve" (1) the complete solution of the structural problem of the steel used.

In the thermal treatment of small samples, the experimenter can impose a heating and cooling cycle determined in advance for obtaining a desired final structure. There is no comparison between the behavior of large masses (ingots) and the local fusion with the rapid heating and very rapid cooling rate (welds); the thermal conditions therefore depend upon the nature of the metal, its mass, etc. It is interesting to study the thermal cycle and to determine the effect of different factors which may intervene.

Some theoretical studies have been undertaken to solve the various cases in practice of the thermal distribution in steel ingots during cooling represented principally by those of Seizo Saito on "The thermal distribution in ingots during cooling" and (2) a theoretical work of great interest on "Internal cooling of homogeneous and isotropic bodies" by J. Mercier and P. Michoulier (3).

The latter have considered very specially the case of industrial thermal treatment of pieces of various simple forms, plates or bars brought to the temperature of anneal (1000°C) and cooled in air or quenched rapidly.

The work of A. Schak (4) is also cited, who gives the methods of making "Practical calculations of non-permanent heat transmission" e.g. with continuous variation of heating and cooling.

In the field that we are interested in directly: Fr. Politz (5) studied oxyacetylene welding of castings for which several tests were made of cast bars which were heated at one end nearly to a point of fusion for 90 seconds. He observed that the heating curve was linear, but that the cooling rate was an exponential curve.

F. Herman (6) made an experimental study by using thermocouples and determined the temperature distribution at different distances from the center of the weld. He could, therefore, compare the two principal methods of oxyacetylene welding; the "classic method", and the "backhand method". He found for the same distance from the center the maximum temperatures attained in the "classic" method were slightly higher than for the "backhand" method.

A very complete experimental study has been made by H. Bornefeld (7). This author made a comparative study of the thermal partition and the thermal efficiency of the different welding methods; oxyacetylene torch, electric arc, atomic H_2 and arcogen process (torch and arc).

Finally, we call to attention a theoretical work of outstanding value of J. Pincon (8) on the thermal distribution in arc welds for the case of plates, sufficiently thin that the various points of the normal common to the plate are at the same temperature at every instant.

The study which we present is divided into two very distinct parts: in the first, theoretical part we consider the distribution of temperature for the case of fixed local fusion of an infinitely long plate or bar, then we examined the problem for the whole plate as the zone of fusion moves. The curves resulting from the calculations represent the general course of the phenomenon.

In the second part we give our experimental results. The differences obtained between the theory and practice indicate the approximations made to arrive at a solution for the complex differential equations given by the theory.

Finally the conclusions drawn from the experimental studies bring into evidence the effect of: processes and methods of welding, the nature of the metal (thermal conductivity) and finally, the dimensions and shape of the pieces (9). These conclusions have been predictable theoretically by means of the calculations and exactly by experience.

Part 1
Theoretical Study

The temperature distribution in pieces assembled by welding can be theoretically considered in the following manner. A point in the piece at ambient temperature is caused to rise rapidly to the fusion temperature θ_f; at this moment the heat source is displaced with a velocity V which we shall consider as constant.

During the continuous rectilinear displacement the moving point will be maintained at fusion temperature.

A priori, the resolution of such a problem is complex. We must, therefore consider a much more simple case: distribution of temperature around a point brought to a point of fusion and the case of a bar melted at one end, which makes possible determination of the limits of possibility in the treatment of the problem as a general one.

We, therefore, arrive at the conclusion that the theory cannot give the general course of the phenomenon for every case that may be considered, since for the resolution of the differential equations obtained, we will be required to make certain approximations or to disregard certain factors which may modify the position of the real curves, without affecting their general form.

First Case - Fusion of the end of a long bar.

Imagine a long bar of cross section S, in which one of the ends is melted; all the heat flows to the opposite face A B, which is at ambient temperature θ_o, just as if it were a tube.

The problem resolves itself into a study of the cooling at each point, as a function of the time. We will neglect losses due to convection and radiation as well as thermal variations accompanying changes of state and we will not consider the conductivity Z of the metal. We shall apply the Fourier theory to constants of heat, which traverses a section $A_1 B_1$ at distance x from the surface AB; t the time from the start of cooling, δ the density of the material, c its specific heat. (See Fig. 1).

Assume that loss of heat across a section of the bar is proportional to the temperature drop during time, dt.

There will enter in $A_1 B_1$ an amount of heat:

$$dQ = -n \cdot s \cdot \frac{\delta \theta}{\delta x} \cdot dt$$

There will flow out of $A_2 B_2$ an amount of heat:

$$dQ^1 = -n\, s \left(\frac{\delta \theta}{\delta x} + \frac{\delta^2 \theta}{\delta x^2} \cdot dx \right) dt$$

and writing that the difference $dQ^1 - dQ$ is proportional to the temperature drop we obtain:

$$n \frac{\delta^2 \theta}{\delta x^2} = \delta c \frac{\delta \theta}{\delta t}$$

assuming that $\frac{c\delta}{n} = 2a^2$ we obtain a differential equation as a function of variables x and t:

$$\frac{\delta^2 \theta}{\delta x^2} = 2a^2 \frac{\delta \theta}{\delta t}$$

which is a Laplace type of equation.

The limiting conditions are:

$$\theta = \theta_f, \text{ for } t = 0.$$

$$\theta = \theta_o, \text{ for } x = 0.$$

The general solution is:

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

in which,

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

The Laplace functions can be determined from tables (table of Laplace functions can be found in "Errors and Least Squares" by M.R. Delteil, page 153 (1930, editor, Gauthier-Villars).

Application of the equation to steel:

$\theta_o = 25 \qquad \theta_f = 1500$

$\delta = 7.80$

$c = 118 \times 10^{-6} \qquad 2a^2 = \frac{c\delta}{n} = 1.15, \quad a = 0.76$

$n = 800 \times 10^{-6}$

The relation:

$$\phi\,(u) = \frac{2}{\sqrt{\pi}} \cdot \int_o^u e^{-\omega^2} \cdot du = \frac{\theta - \theta_o}{\theta_f - \theta_o}$$

determines therefore the variation in θ for each value of x; in other words at different distances from the fused surface.

The curves of Fig. 2 show this thermal distribution for a bar of steel.

The curves of Fig. 3 show the effect of the nature of the metal on this distribution. They have been calculated for the case of copper.

In this case the differential equations remain the same, the value of $a = \sqrt{\frac{c\delta}{2n}}$ only, changes ($a = 0.23$) as follows:

$$u = \frac{0.23}{\sqrt{2t}} \cdot x$$

which allows us to write as for steel:

$$\phi\,(u) = \frac{2}{\sqrt{\pi}} \cdot \int_o^u e^{-u^2} \cdot du = \frac{\theta - 23}{1.083 - 23}$$

Speed of Cooling

The rate of cooling is given by the curve $\theta = f\ (t)$:

$$V = - \frac{\delta \theta}{\delta t} = (\theta_f - \theta_o) \quad \frac{2}{\sqrt{\pi}} \cdot \frac{u}{t} \cdot e^{-u^2}$$

These curves are shown for steel in Fig. 2.

An interesting value to know is the maximum rate of cooling. This has a locus for

$$\frac{dV}{dt} = 0 , \quad \frac{d^2\theta}{dt^2} = 0 \text{ (inflection point of the curve } \theta = f(t) \quad ,$$

$$\frac{d^2\theta}{dt^2} = (\theta_f - \theta_o) \frac{2}{\pi} \; e^{-} \; \frac{a^2x^2}{2t} \quad x \quad \frac{ax}{t^2} \left(\frac{\sqrt{2} - 1}{\sqrt{2}} - \frac{a^2x^2}{2t} \right) = 0$$

the maximum for $a^2x^2 = 0.60t$

for steel: $a^2 = 0.575$

$$x^2 = 1.04t \qquad (1)$$

the locus of the maximum is given by a parabola drawn in Fig. 4 b.
The value of the maximum is given as a function of t

$$(V_m)_t = (\theta_f - \theta_o) \frac{2}{\sqrt{\pi}} \cdot \frac{0.54}{t} \cdot e^{-0.30}$$

therefore:

$$(V_m)_t = \frac{K}{t} \quad \text{where K is a constant.}$$

$(V_m)_t$, is inversely proportioned to the time considered

$$\theta_f - \theta_o = 1475$$

for

$$(V_m)_t = \frac{660}{t}$$

We can express V_m as a function of x by means of relation (1) above, giving:

$$(V_m)_x = \frac{686}{x^2}$$

The maximum rate therefore diminishes very rapidly (proportionally to à $\frac{1}{x^2}$) as we go away from the layer superficially fused.

For copper (a = 0.23) we obtain

$$x^2 = 11.3t$$

$$(V_m)_t = \frac{475}{t}$$

$$(V_m)_x = \frac{5.375}{x^2}$$

The curves of Fig. 4 a and 4 b give the variations of the maximum rate V_m f (t) (hyperbolas of fig. 4 a) and $V_m = \phi$ (x) (parabolas of fig. 4 b) for bars of steel and copper. They show the effect of the nature of the metal on the lateral thermal distribution.

We can deduce from these considerations, the isoclines or lines of equal rate of cooling which permit the establishment of the zones which can attain critical temperatures and rates, such as for steel where profound physico-chemical changes take place.

It will also be easy to deduce the form of the isochronic (equal time) curves for the times t_1 $t + \Delta t$. These curves are normal to the isotherms, they will be specified in the experimental portion of our paper.

This first example, intentionally simplified, only gives an approximate idea of the thermal distribution in a bar.

Second Case - Thermal distribution around a point.

The thermal equilibrium in a plate heated at point O (Fig. 5) with the condition that the point is maintained at a constant temperature, can be given by application of Fourier theory.

The isotherms are circles by reason of symmetry, for which the center is O.

Let x be the distance from the center of the circle A; ϵ the thickness of the plate, and E the loss of heat by convection.

There will then enter the circle A a quantity of heat:

$$dQ = -2\pi x \; \epsilon n \; \frac{\delta \theta}{\delta x} \; . \; dt$$

n being the conductivity of the metal:

There will flow out of the circle B (x + dx) a quantity of heat:

$$dQ^1 = 2 \pi \mathcal{E} (x + dx) \cdot n \left[\frac{\delta \theta}{\delta x} + \frac{\delta^2 \theta}{\delta x^2} \cdot dx \right] dt$$

There will flow out of the lateral face:

$$dQ^{11} = 2 \pi E x \cdot dx \ (\theta - \theta_o) \ dt$$

Expressing this as a stationary state, the thermal equilibrium is given by the differential equation:

$$x \frac{\delta^2 \theta}{\delta x^2} + \frac{\delta \theta}{\delta x} = \frac{E}{n \mathcal{E}} \ n \cdot (\theta - \theta_o)$$

assume:

$$b = \frac{E}{nc}$$

and the equation may be written:

$$\frac{\delta^2 \theta}{\delta x^2} + \frac{1}{x} \frac{\delta \theta}{\delta x} - b \cdot \theta = 0$$

This equation cannot be integrated by means of Bessel and Hanckel series.

The general solution is of the form:

$$\theta = AJ\ (u) + B\ K\ (u)$$

in which:

$$u = \sqrt{\frac{E}{n \epsilon}} \cdot x$$

the functions J (u) and K (u) are given in tables; A and B are constants which can be determined by conditions at the limits.

These functions have been considered and discussed in the work of J. Mercier and P. Michoulier (3).

A solution of the problem cannot be given except for particular cases.

Third Case - Welding of a plate of infinite dimensions.

The problem is complicated by the displacement of the source of heat. M. Pinczon (8) has given an excellent solution of the problem for the case of an arc weld on a thin plate. The conditions imposed for the author's calculation are that the various points of the normal to the two faces are at every instant at the same temperature. In welds this condition is almost realized for thicknesses of less than 2 mm; the author also neglected in his calculations the effect of radiation and convection from the exterior faces.

With these approximations, a point of the coordinates x, y of the plate, when the source advances following the line ox, with velocity v, is related to the temperature by the differential equation:

$$\frac{\delta^2\theta}{\delta x^2} + \frac{\delta^2\theta}{\delta y^2} = 2a^2 \frac{\delta\theta}{\delta t} \qquad \text{(A)}$$

$2a^2 = \frac{c\delta}{n}$ is already defined.

The limiting conditions are: $\theta = \theta_o$ for $t = 0$ and $x \geq 0$, but different for v t and y, entirely:

$$\theta = \theta_f, \quad x = vt, \quad y = 0 \text{ and } t > 0$$

The general solution is given by:

$$\theta = 1/2\ \theta_f \left[\phi(z+p) + e^{-4pz}\ \phi(z-p)\right] \phi(u) \qquad \text{(B)}$$

$$\text{for } z > 0$$

and

$$\theta = 1/2\ \theta_f \left[e^{-4p\,|2| + p\,|z|}\ \phi(|z|+p) + \phi(|z|-p)\right] \phi(u) \qquad \text{(C)}$$

$$\text{for } z < 0$$

the letters z, u and p are functions of the time t and the coordinates x and y.

$$z = \frac{a(x-t)}{\sqrt{2t}}$$

$$u = \frac{ay}{\sqrt{2\,t}}$$

$$p = av\sqrt{\frac{t}{2}}$$

The other part, ϕ (z) is the Laplace function:

$$\phi(z) = \frac{2}{\sqrt{\pi}} \cdot \int_{z}^{\infty} e^{-z} \cdot dz$$

The author has also shown that for the case of a very high rate of welding, $v > 0.5$ cm./sec.
The equation (B) is written simply as

$$\theta = \theta_f \; e^{-4pz}$$

This results in an error imposed on the function ϕ (z) which determines the range of terms for the devolopment in a series of this function.

By replacing the letters by their values:

$$\theta = \theta_f \; e^{-\frac{c\delta}{n} \cdot v\,(x - vt)}$$

which permits determination of x for a given rate , at different instants t, and consequently the thermal distribution ahead of the weld at the time welding ceases.

Study of the isothermal curves.

1. For the case of local fusion at a fixed point of the surface of an infinite plate, the isotherms are concentric circles by reason of symmetry. The radii of the concentric circles as a function of the temperature are given by the relation

$$r = \frac{\theta_f}{\theta} \; \frac{\sqrt{2t}}{a}$$

which is written as $u = \frac{a\,y}{\sqrt{2\,t}}$

with

$$2\,a^2 = \frac{c\,\delta}{n}$$

2. If the zone of fusion moves with a constant velocity v (for steel welds), the isothermal curves are deformed, they are elongated in the direction of the weld.

The envelope of the isothermal curves is given by the parabola:

$$y^2 = \frac{2x}{a^2 v} \left(\frac{\theta_f}{\theta} \right)^2$$

obtained by elimination of t from the two equations:

$$x = v\,t \quad \text{and} \left(\frac{\theta_f}{\theta} \right) = \frac{a\,y}{\sqrt{2\,t}}$$

The envelope curves may also be conics but not elipses.

When the welding is sufficiently slow there may be established a quasi-stationary state; the envelope of the isotherms may then be two straight lines (degenerated parabola) parallel to the line of the weld.

We can arrive at the general formulae of the envelope, the direction of elongation of the isotherms when the velocity of the welding varies.

Fig. 6 represents the envelopes of the isotherms of two oxyacetylene welds made with a speed of .04 cm./sec. and at .20 cm./sec.

These results, predicted by the calculations, were obtained in practical welding tests on sand-surfaced plates. The form of the isotherms could be followed by the color changes due to metal heat treatment. Fig. 7 shows one such test, it indicates the form of the isotherm for a plate heated locally and the isotherms for a weld which has not attained the quasi-stationary state (elipse) and for one weld in which the state has been attained (parallel lines).

We see plainly the effect that speed of welding has on spreading out the isothermal curves.

SECOND PART

Experimental Studies

The experimental study allows us to state precisely the curves for thermal distribution, the general trend of which has been given by the calculations.

Reciprocally in a number of cases, the theory aids us in correcting or in extrapolating a curve beyond experimental limits. This study has for its goal the determination of the effect of the following factors on the thermal distribution in welds:

1. Thickness and shape of the samples.
2. Method of welding, oxyacetylene or electric arc.

3. Mode of welding "classic" or "backhand".
4. Nature of the metal.

Experimental methods

The experimental method employed was one of determination of temperature with thermocouples at different distances from the line of welding, at the surface and in the metal mass.

(a) Thermocouples.

The couples used were wires of Pt and Pt Rh (10% Rh) of 0.20 mm. diameter. Very abrupt changes in temperature occur principally in the high temperature zone and it was therefore necessary to avoid as much as possible the thermal inertia of the weld of the couple. The very small mass of the weld of the two wires was placed at the head of a capillary tube of silica and made direct contact with the metal plate.

For determining temperature in the metal mass the couples were placed into drilled holes of 2 mm. diameter at different distances from the axis of the weld, depending upon the welding method, the depth of the holes being one-half the thickness of the samples.

The couples were connected to a double mirror galvanometer. The ray reflected from the first mirror was received on a cylindrical drum with horizontal axis (10 cm. diameter) which was actuated by a clock-work motor at a speed of 23 minutes per revolution; the drum was supplied with photographic paper. The galvanometer and the drum were placed under a light-tight hood.

The second, auxiliary mirror carried on the same suspension wire supplied a spot of light which could be followed on a separate, translucent scale thus allowing visual inspection of the phenomenon while it was being recorded.

Study of Different Factors

1. Method of welding, oxyacetylene and electric arc.

The comparative study of the thermal distribution for welds made with torch and arc on samples of the same shape (plates and bars) and the same nature (steels).

The welds were made by following accepted rules, e.g. with specifications determined by the torch and a function of the thickness and the form of the material. The electrodes used were of industrial type, and the arc welds were made with the electrical characteristics which are well defined.

2. Mode of welding.

For the study of this factor, we have compared the two methods, "classic" and "backhand" oxyacetylene welding which are practiced with ordinary steels (Note - for a description of these methods see in particular "Treatise on Autogenous Welding" by Granjon and Rosenberg).

The other metals and alloys were welded according to their proper industrial procedure in welding.

3. Thickness and shape of the samples.

For the study of these factors welds were made:

(a) on plane plates 50 x 50 cm. (to avoid the effects of the edges) and 10 and 5 mm. thick.

(b) on square bards 10 mm on sides and round bards of 10 and 5 mm. diameter.

For all the samples the temperature on the surface, on the face opposite to the weld and in the middle (half thickness) was measured for the welds on plates and square bars 10 mm. thick.

For determining surface temperature the couple wires of 2/10 mm. diameter were welded directly to the plate or bar by means of a small spot welder.

In the case of the plates the welds were made for a length of 20 cm., the couple being placed along a perpendicular to the line of the weld, passing through the middle of the line, or 10 cm from the starting point; we call this "the line of the couples".

4. Nature of the metal.

The nature of the metal is defined by its coefficient of heat conduction β :

$$\beta = \frac{n}{c\delta}$$

c = specific heat.

δ = density.

n = conductivity.

Tests were made on the following metals or alloys:

Mild steel, 0.10 carbon $\beta = 0.865$
Austenitic Ni-Cr steel (18-8 type)
Pure copper, weldable, (*); $\beta = 9.13$
Pure aluminum; $\beta = 7$

(*) The pure, weldable copper is of completely deoxidized material. When it has even a low O_2 content (.05%) the O_2 is a factor in the unweldability of this metal.

The welds on these metals and alloys were made under the following conditions:

(a) Welds on steels.

The oxyacetylene welds on mild steel were made with a torch delivering 100 liters of acetylene per hour per mm. thickness of plate. The average speed of welding was

125 cm. per hour for "classic" weld on 10 mm. thick plate.
160 cm. per hour for "backhand" weld on 10 mm. plate.
250 cm. per hour for "classic" weld on 5 mm. plate

The austenitic 18-8 steel was welded with a rod giving a deposit of mild steel with a gas volume of 1000 liters per hour in the torch for the 10 mm. plate.

The backhand method was used, the welding speed being 150 cm. average per hour.

The electric arc welds on 10 mm. thick plates were made in three bead runs, the first (at the bottom) was made with a mild steel, 4 mm. diameter rod, the two other beads being made with the same rod material, but of 3.3 mm. diameter.

The coating composition was:

Fe_2O_3	=	58%
$K_2O, 3SiO_2$	=	21%
SiO_2	=	5.2%
Al_2O_3	=	5%
H_2O, CO_2	)	remainder

Welding conditions for arc welds were:

4 mm. rods	115 amps, 18 volts
3.3 mm. rods	90 amps, 19 volts

(b) Oxyacetylene welds on plates of copper and aluminum.

For making the welds on thick plates (10 mm.) of copper it was necessary to use two torches of 2000 and 2500 liters capacity, the first serving as pre-heating torch and the second for actual welding.

The determination of temperatures during preheat showed it to be necessary to attain a uniform temperature of about 500°C. over the whole plate in order to be able to start welding.

The welds on copper were made with the classic method, the welding torch being preceded by the preheating torch. The speed of welding, with uniform acceleration was 100 cm. per hour, on the average.

For the oxyacetylene welds on aluminum, preheating is also necessary. A single welding torch of 2000 liters capacity served for this operation. For the welding it was necessary to attain a temperature between 300° and 350°C, over the whole plate.

The welds were made by the classic method with a speed of uniform acceleration. The average speed was 100 cm. per hour counting the time of preheating.

. . .

For every test it was possible to obtain a curve of $\theta = f(t)_x$ for a point at a distance x from the weld.

From these curves we have obtained other curves by graphic construction which permitted the determination of the effect of different factors. In particular:

(a) The curves for maximum temperatures projected on the plane of the thermocouples $\theta_m = f(t)$.

(b) The derived curves, $V = \frac{\delta\theta}{\delta t}$

(c) The isochronic curves made possible the determination of the curve $\theta = f(t)_o$ of the plane passing through the line of the weld $(x = 0)$.

(d) The isotherms corresponding to a position defined by the torch or arc, and consequently the family of isotherms dependent upon the displacement of the source of heat.

From all these curves we could determine the curves $\theta_m = \phi(V_m)_x$ for variable x which when superposed on characteristic quenching curves of the steel welded made possible the drawing of conclusions of importance as to the physico-chemical modifications produced by welding.

1. Maximum temperature curves.

The recorder produced the curve $\theta = f(t)_x$ by definition for the plane passing through x and parallel to the weld line. When the source is displaced with a constant velocity, this curve is displaced with the same velocity in the plane and remains in the plane.

For every value of x, the curve $\theta = f(t)$ passes through a temperature maximum. This maximum is attained when the fusion heat source has passed beyond the line of the thermocouples, moreover, this maximum is displaced with x following a definite law $x = \phi(t)$. Consequently the curve of temperature maxima for the entire procedure is a one sided curve, defined by the functions

$$\theta_m = f(t,x) \text{ and } \quad x = \phi(t)$$

The curves $x = \phi(t)$ obtained experimentally, fixed with respect to the source of heat in reference to the line of the thermocouples at the moment when the maximum temperature is attained, are the horizontal projections of the one sided curves of the temperature maxima; for the two processes of welding, oxyacetylene (classic and backhand) and electric arc, these curves are represented in Fig. 8. The projection of the curve of the temp. maxima on the plane normal to the line of welding gives the curves $\theta_m = f(x)$, these made possible drawing the first conclusions as to the influence of the various factors which we proposed to study.

The curves of Figs. 9, 10, 11 show the trend of the curves, $\theta_m = f(x)$ for oxyacetylene welds made by the classic method on plates and bars of steel and copper and aluminum of different thickness and shape.

Fig. 12 shows the same curves for an electric arc weld on ordinary mild steel.

11. Curves of Speed of Cooling.

The curves of speed of cooling $V = \frac{\delta\theta}{\delta t}$ were constructed graphically by the method of tangents (method used by P. Chevenard, cf; dilatometric analysis of materials by Dunod Paris, 1929). For determining a point on the derived curve $\frac{\delta\theta}{\delta t}$ a line is drawn from the origin parallel to the tangent at a desired point of the curve $\theta = f(t)$ which determines on any straight line parallel to the θ axis a segment for which the value is $\frac{\delta\theta}{\delta t}$ The projection of this segment on the ordinate of the point gives a point on the desired curve of cooling speed.

111. Study of the ixothermal curves.

The calculations indicate that all the isothermal curves are a family of parabolas (real or degenerate) serving as envelopes for the isotherms for a definite position of the torch or arc dependent upon the speed of advancement. The curves for which the parabolas are envelopes are elipses which are completely defined by their two axes.

The major axis of an isotherm for which θ is given by the curve $\theta = f_c(t)$ for the line of the weld its length is equal to segment a b of Fig. 13 for the value $\theta = \theta_f$. The minor axis is determined by the curve $\theta = f_{(x)}$.

The first curve $\theta = f_c(t)$ is obtained by extrapolation of the curves $\theta = f(t)_x$ determined experimentally for different values of x. This extrapolation was made by drawing the isochronic curves for the times t, $t + \varepsilon$, $t + 2\varepsilon$...... up to their intersection with the plane x = 0 (plane of the weld).

The diagram of Fig. 14 shows the isothermal elipses for an oxyacetylene weld (classic method) for a point included on the line of the weld, we may immediately draw the following conclusions:

1. Each curve defines the zone of the plate where the temperature attained is the same or higher than the temperature of the corresponding isotherm.

2. When the source of heat is displaced with velocity v. the family of isotherms at the instant t are displaced at the same speed. The envelope of the isotherms at different given instants gives the family of the isotherms when the source has been displaced for a length equivalent to $y = v.t$ The upper part of the diagram (Fig. 16) represents the isotherms of an oxyacetylene weld when the torch has moved from A to B.

3. For the same procedure and same method of welding, if the speed of advancement of the source varies, the isotherms obtained for the different speeds are homothetic curves, the relation of homothety being the same as the relation of the speed of welding.

The diagram of Fig. 15 represents the isotherms for an electric arc weld for a plate 10 mm. thick. The very different thermal distribution of the two welding processes is evident not only for the lateral thermal distribution but also along the line of the weld itself, where the steep temperature drop ahead of the weld is indicated when the electrode is brought to rest.

The lower part of Fig. 16 represents the isotherms for an electric arc weld between two points.

Results

The results of temperature measurements make it possible to represent the thermal distribution in a plane of a surface $\theta = \phi(x,y)$ such as are given in Figs. 17, 18, 19 the thermal displacement of this surface follows that of the thermal source responsible for the fusion of metal.

On such surface we have drawn:

(a) the experimental curves $\theta = f_x(t)$ for the different values of x.

(b) the isochronic curves $\theta = f_t(x)$ for different values of temperature from this curve was determined a particular curve $\theta = f_o(t)$ for the plane passing through the weld line.

(c) the isotherms $\theta = C^{te}$, the intersection of the solid by the horizontal planes.

After an examination of these surfaces the factors which appear to have a preponderant influence on the thermal state are:

(1) The method of fusion, arc or torch; the arc (Fig. 18) produces a more rapid heating, e.g., as determined by the temperature gradients, and speed of cooling which are far in excess of that for the case of the oxyacetylene welding process (Fig. 17);

(2) The thermal conductivity of the metal and the initial preheat temperature before welding, if the latter is necessary.

This is the case for the thermal conductor metals; copper (Fig. 19) or aluminum, for which the influence of the coefficient of thermal conductivity is in evidence by the widened form of the surface $\theta = \phi(x,y)$ and the influence of the temperature of preheat by an anomaly of the curve $\theta = f_x(t)$ at that temperature (500°C., for copper, 300°C. for aluminum).

(3) The size and shape of the sections assembled by welding, and depending upon whether they extend in two or three directions of space (bars, plates, massive sections) and depending upon the thickness in the case of plates or bars.

The other factors, especially the method of carrying out the welding appear to have only a secondary influence.

This investigation of thermal distribution dominates two other studies of incontestable practical interest.

1. The local heating produces an acceleration of the cooling rate by metallic conduction of heat toward the cooler regions resulting, as a premier consequence, in physical-chemical change; the phenomenon of heat treatment.

2. In the whole of the mass the local heating gives rise to unequal expansion and contraction and as a consequence we have internal stress, deformation, cracking.

We shall consider for a moment the most important problem of physical-chemical change.

Physical-Chemical Changes

The solution of this prime problem requires a knowledge of the characteristic hardening curves for the steel, and the curve $\lambda = f(x)$ the trajectory of a point representing a weld.

The curves determined by our investigation can be applied to determine $\lambda = f(x)$. This function is obtained by eliminating x from the curves of maximum temperature, $\theta_m = f(x)$ and the speed of maximum cooling

$\left(\frac{\partial \theta_m}{\partial t}\right)_x$ at different distances from the axis of the weld.

We then obtain the function:

$$\theta_m = \psi(V_m)$$

The diagram of Fig. 20 gives the 4 curves $\lambda = f(x)$ for oxyacetylene weld on a plate (curve a) and on a 10 mm. square bar (curve b). Curves (c) and (d) show results obtained for the same material with an electric arc weld.

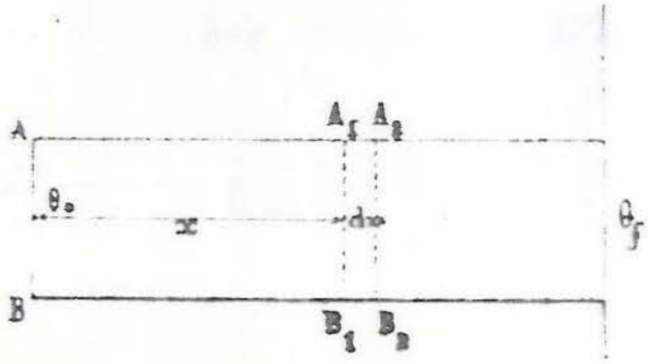

Fig.1 - Fusion at end of long bar.

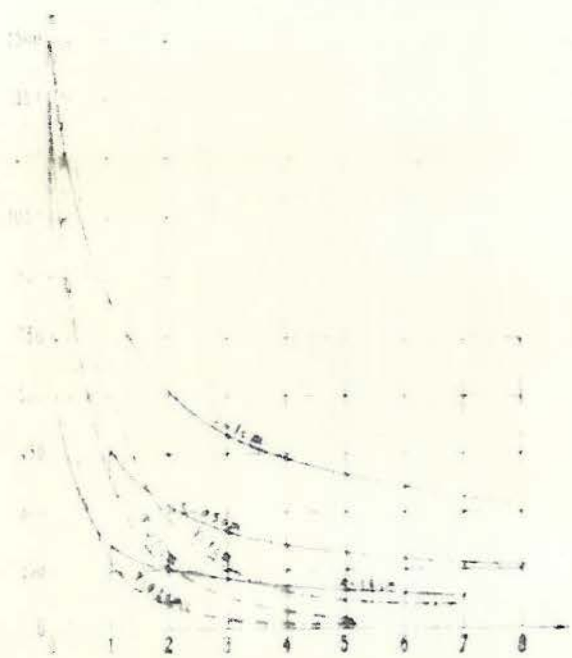

Fig.2 - Temperature distribution in steel bar melted at one end, at distance "X" from melted face.

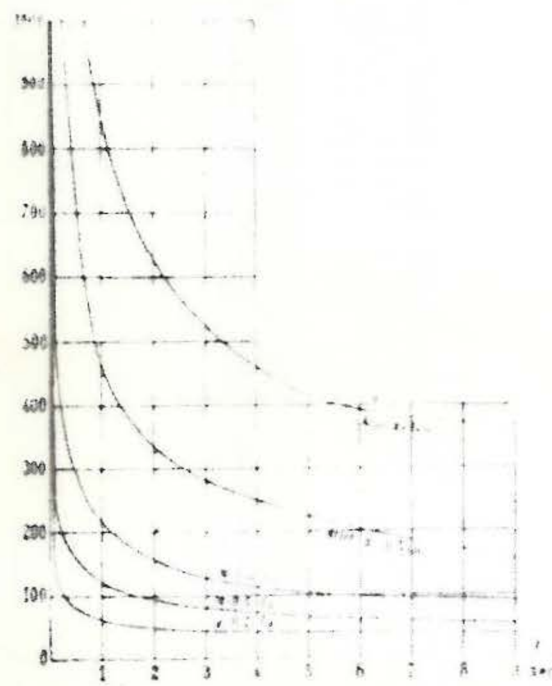

Fig.3 - Comparative curves of temperature distribution for steel and copper. (acier = steel)

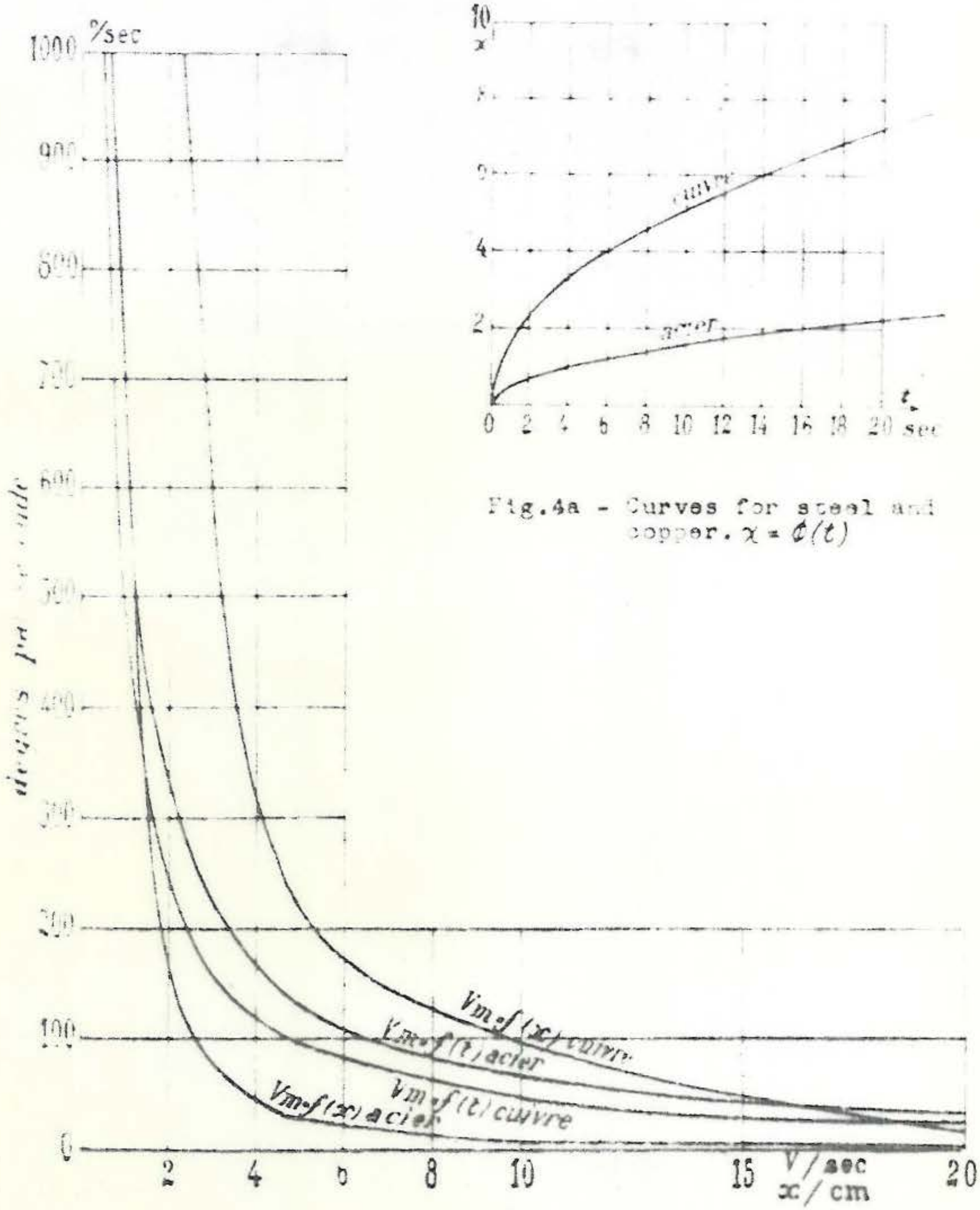

Fig.4a - Curves for steel and copper. $\chi = \phi(t)$

Fig.4 - Variation of maximum speed of cooling for the case of fusion of a bar of steel and copper.(cuivre = copper)

The position of these curves in relation to the characteristic hardening curves determines the nature of the heat treatment (quench) (martensitic or lower quench) and also the extent of the physical chemical changes.

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and D. Seferian.

Bibliography

1. A. Portevin and P. Chevenard - Rev.Met., 18, 717 (1921)

2. Keizo Sato - Supplement to Metallographic Notes Ecole de Fonderie (A. Portevin).

3. J. Mercier and P. Michoulier - Rev.Met., 4, 171 (1929).

4. A. Schack - Arch Eisenhutt., 7, 357 (1927), Rev.Met., 4, Ext. 169 (1929)

5. Fr.Polity - Stahl v. Eisen, 45 693 (1925).

6. F. Hermann - Schweissen u. Schneiden, page 20 (1933).

7. H. Bornefeld - Technische Zeitschrift fur praktische Metallbearbeitung 1/2, 3/4, 4, 14-52 (1933).

8. J. Pinczon - Science et Industrie 234, 316 (1933).

9. A. Portevin and D. Seferian - C.R. Acad.des Sciences 199, 34 (1933).

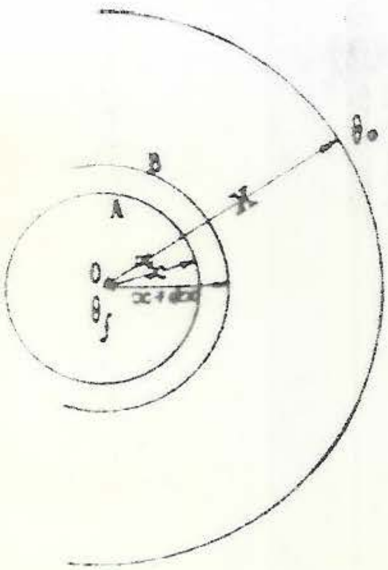

Fig.5 - Thermal equilibrium in a heated plate.

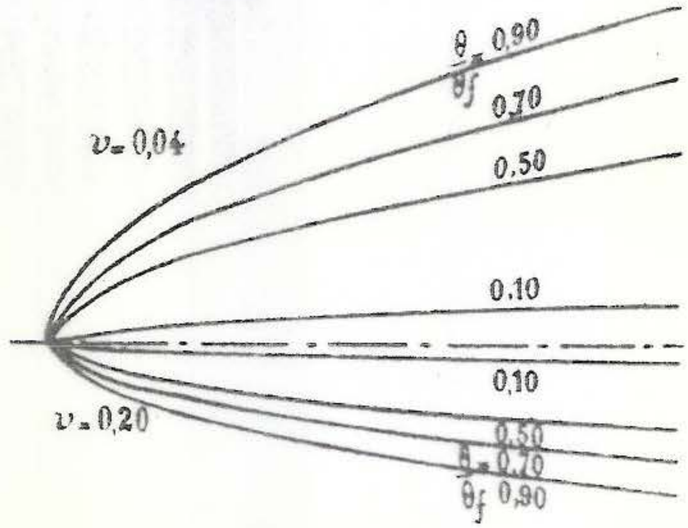

Fig.6 - Effect of speed of welding on distribution of isotherms.

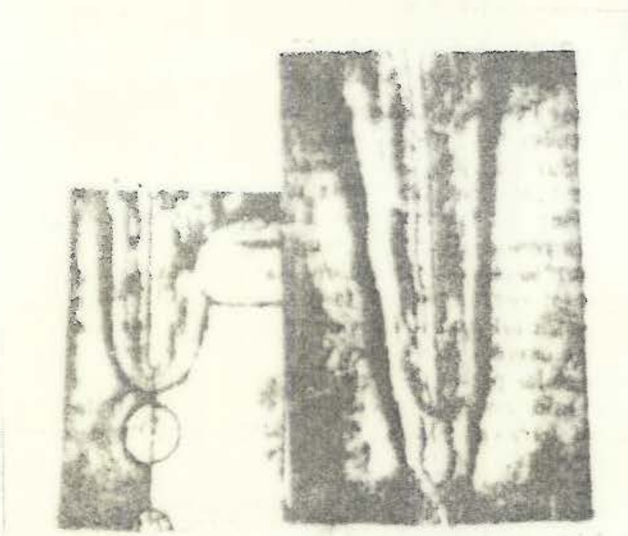

Fig.7 - Isothermal envelopes observed for different practical cases of fusion.

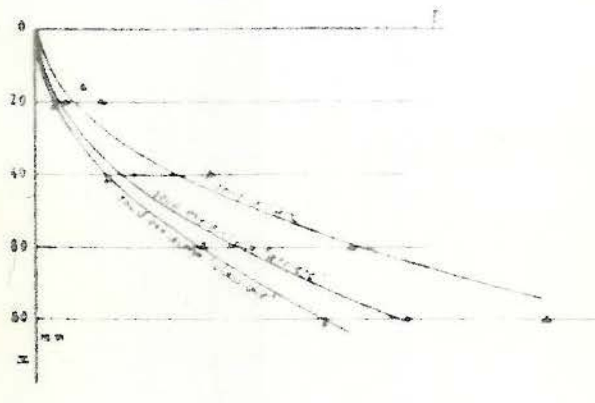

Fig.8 - Loci of maximum temperatures, for different welding methods experimentally determined. (top to bottom, arc, backhand-gas, classic-gas welding).

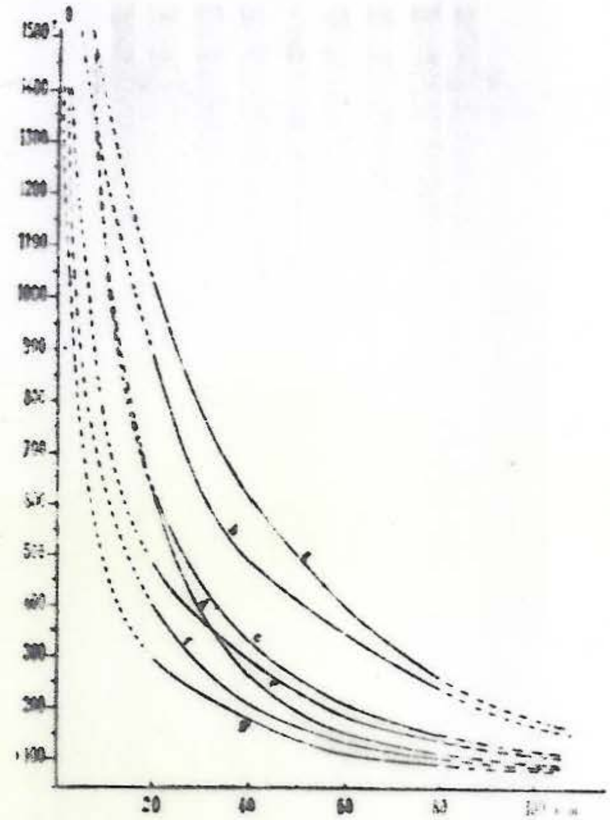

Fig.9 - $\theta_m = f(x)$ curves for oxy-acetylene welding of mild steel (classic method). 10 mm. thick plates with temperature measured at mid-thickness (a), and measured at the surface (b), 5 mm. thick plate (d), 10 mm. square bar, temperature taken at mid-thickness (c) and at surface (d), 10 mm. and 5 mm. round bars (f,g).

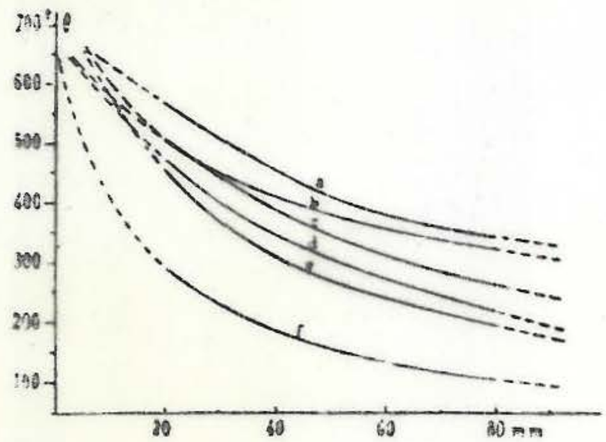

Fig.10 - $\theta_m = f(x)$ curves for oxy-acetylene welding of copper. Plates 10 mm. thick with temperature taken at mid-thickness (a), at the surface (b), 5 mm. thick plate (d), 10 mm. square bar (c,e), 5 mm. round bar (f).

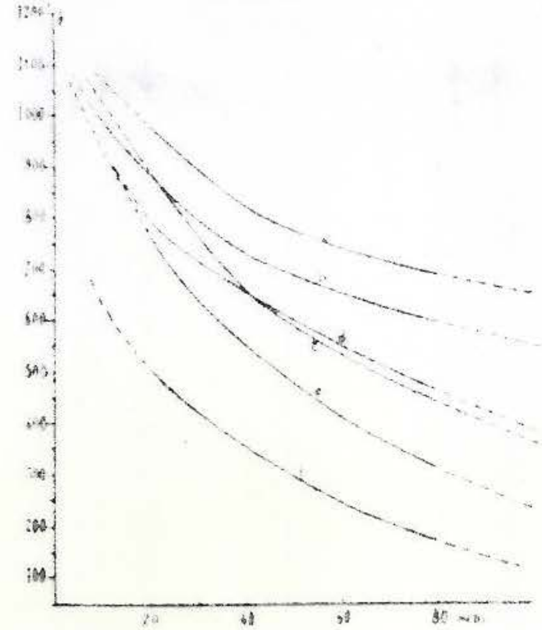

Fig.11 - $\theta_m = f(x)$ curves for oxy-acetylene welding of aluminum. (same conditions as in Fig.10).

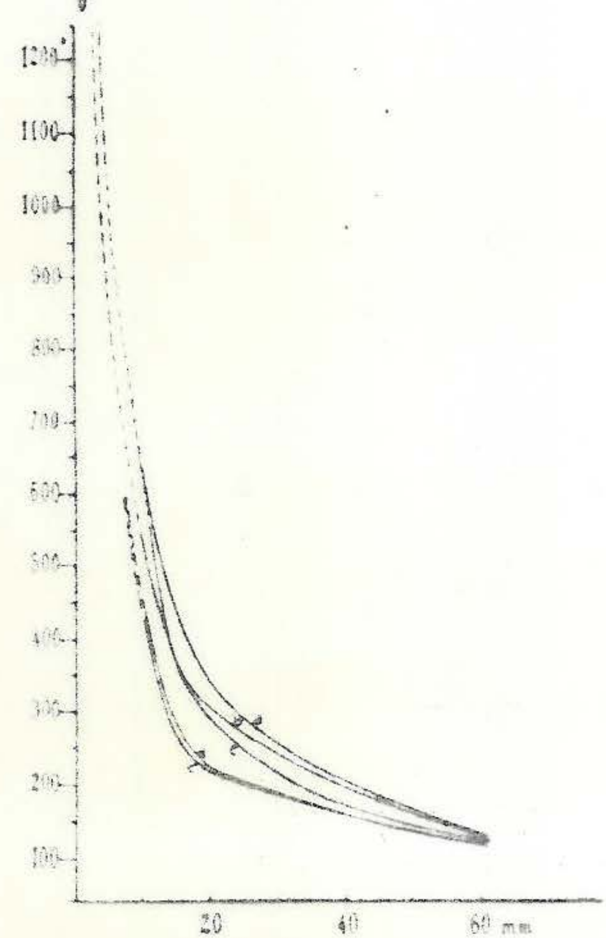

Fig.12 - $\theta_m = f(x)$ curves for electric arc welding of mild steel. Plates 10 mm. thick, temperature taken at mid-thickness (a), at the surface (b), 5 mm. plate (c), 10 mm. square bar (d,e).

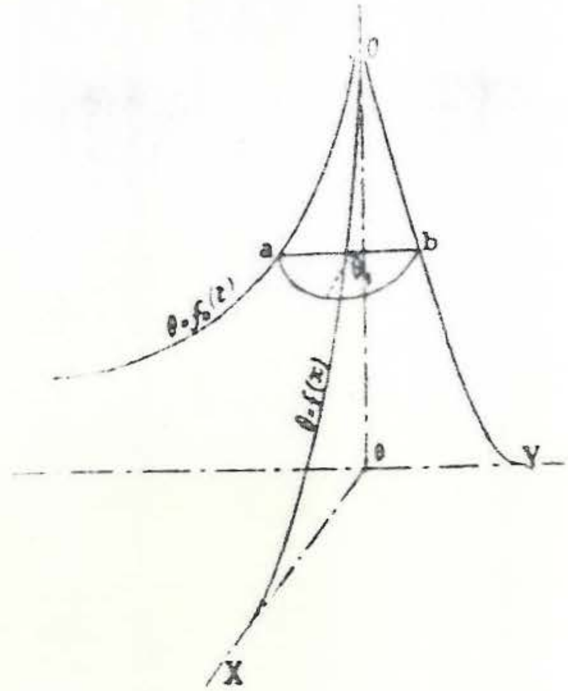

Fig.13 - Method of determining isotherms.

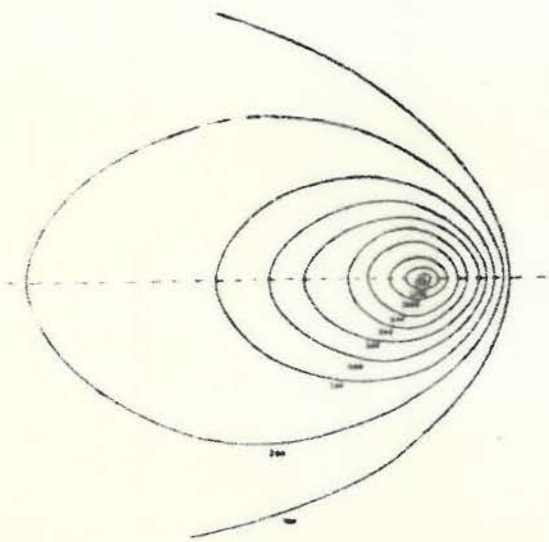

Fig.14 - Isotherms at a given instant for oxy-acetylene welding (classic method) of 10 mm. thick, mild steel plate. Projection of the isotherms on the plane of th plate.

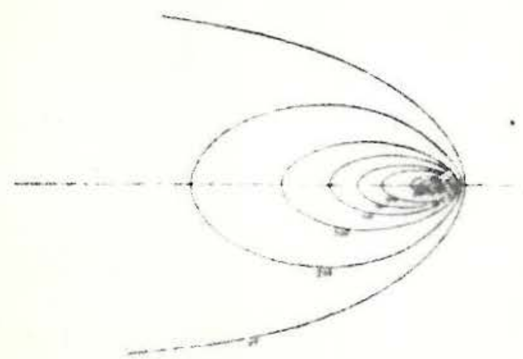

Fig.15 - Isotherms at a given instant, for the electric arc welding of 10 mm. thick, mild steel plate.

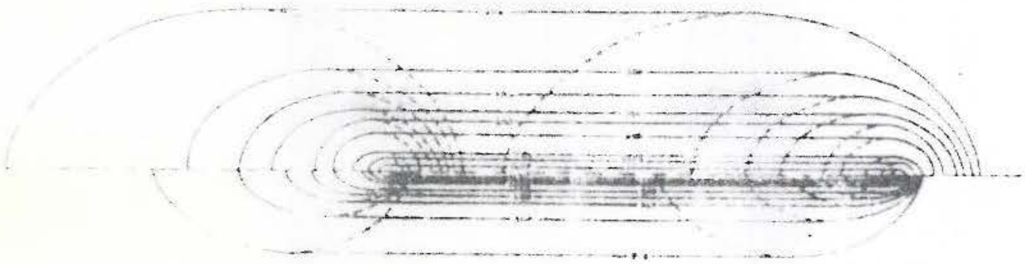

Fig.16 - Isothermal envelopes for oxy-acetylene (upper curves) welding at two given instants; equilibrium having been established previously.

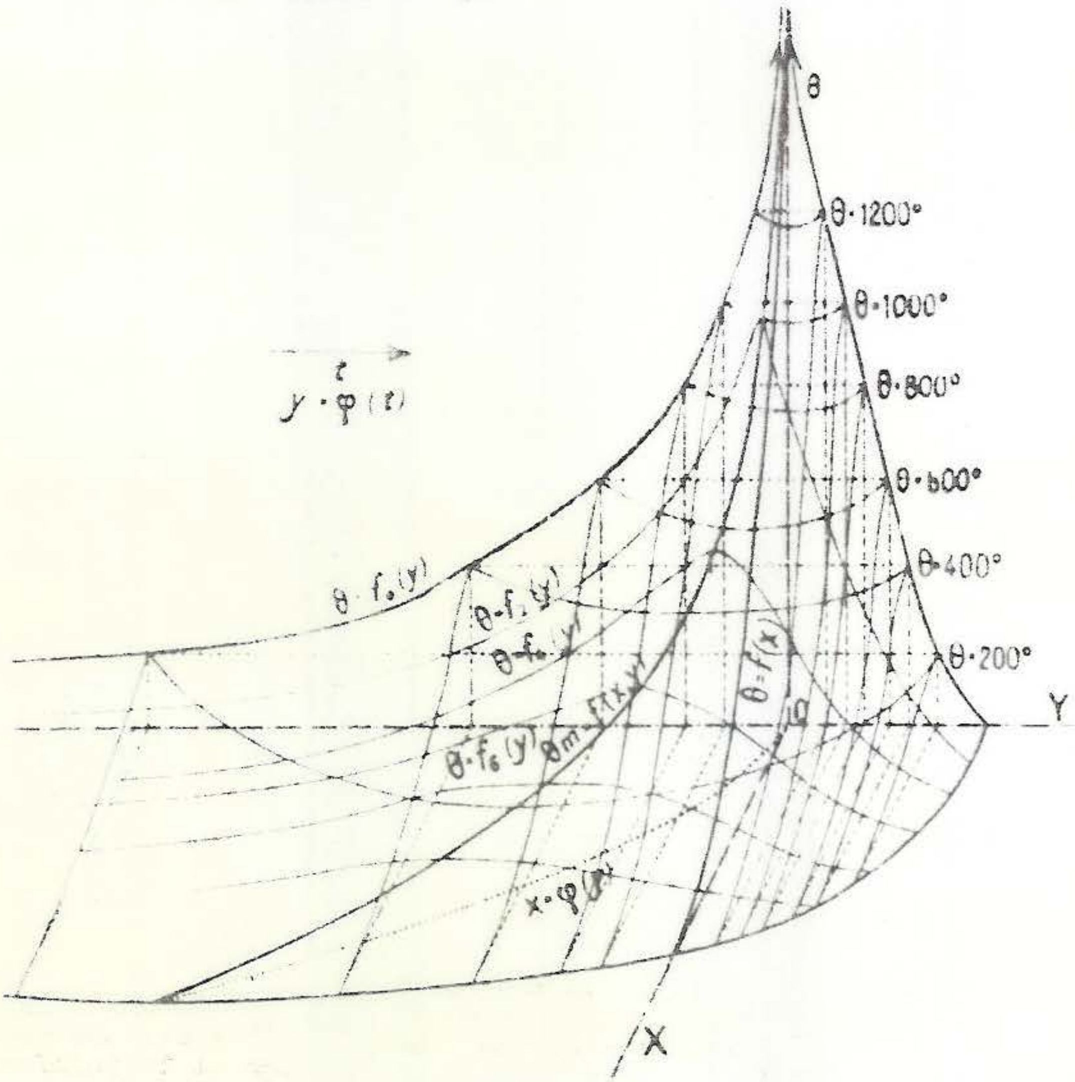

Fig.17 - Thermal surface for oxy-acetylene welding of 10 mm. thick, mild steel plate (temperature measured at mid-thickness). The surface contains the experimental curves $\theta = f_x(y)$, the isochronic curves; the maximum temperature curve $\theta_m = f(x, y)$, its projection on the plane $x = \phi(y)$ and the isotherms.

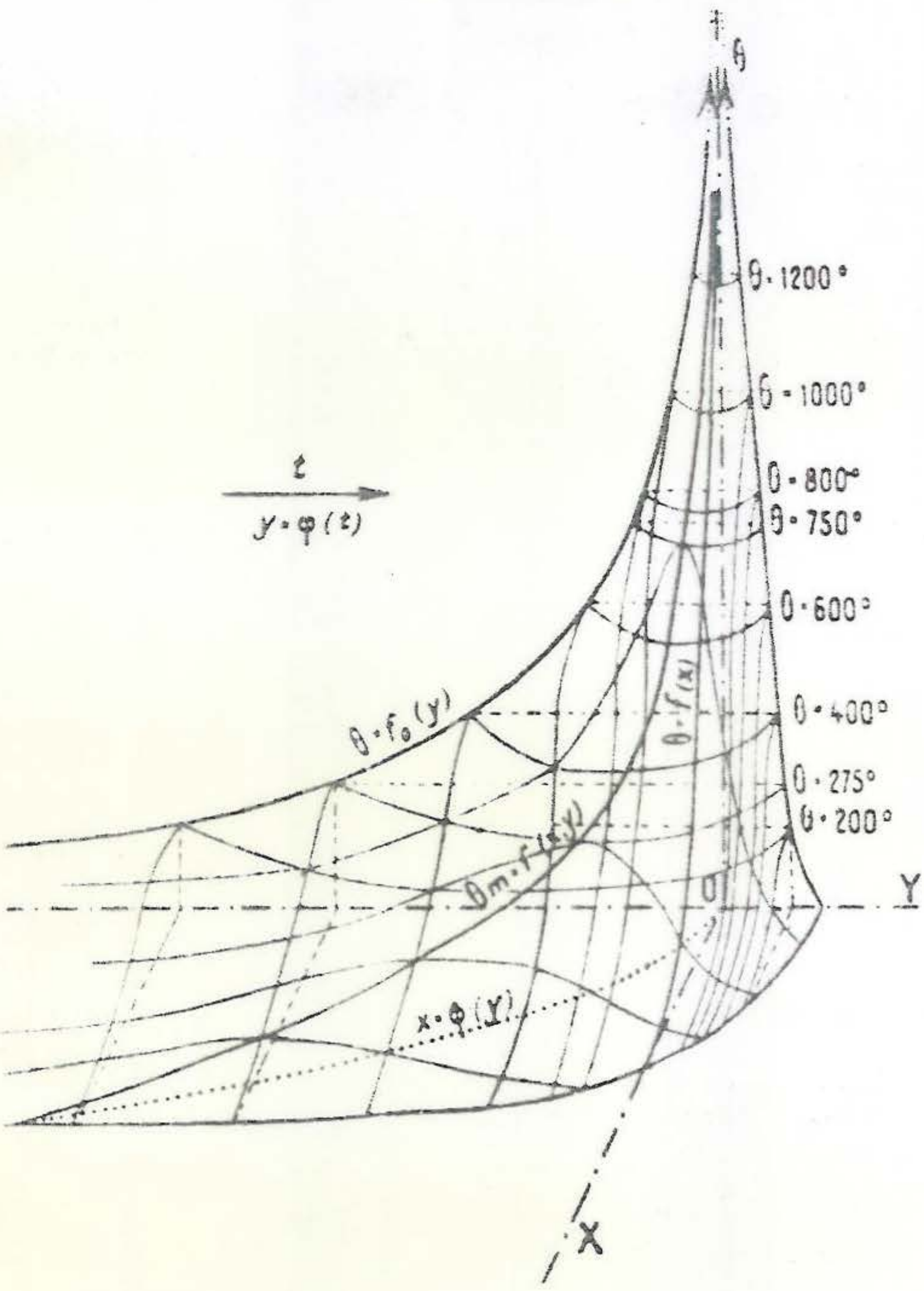

Fig.18 - Thermal surface for electric arc welding of 10 mm. thick, mild steel plate.

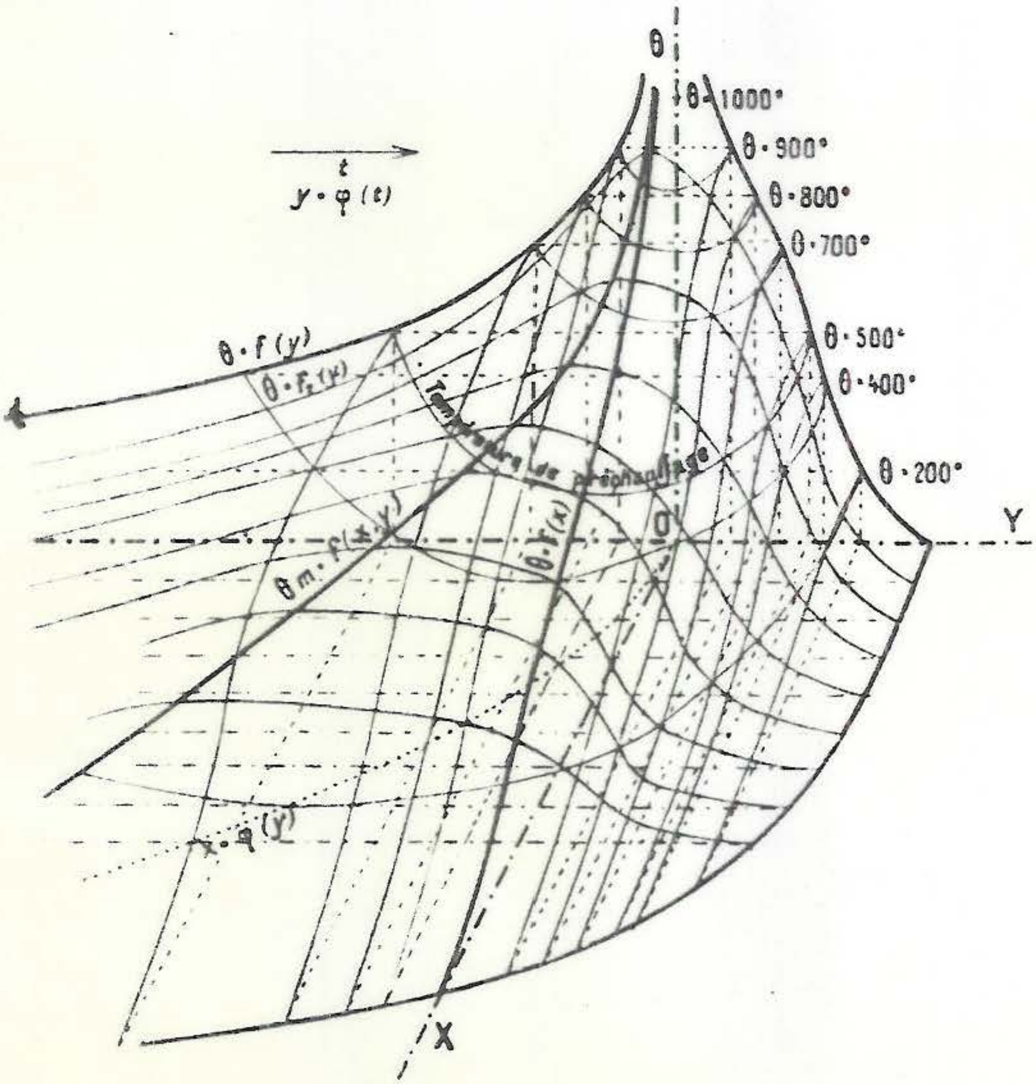

Fig.19 - Thermal surface for oxy-acetylene welding of copper plate 10 mm. thick. The preheating temperature is indicated by an anomaly of the $\theta = f_0(y)$ curve at 500°C.

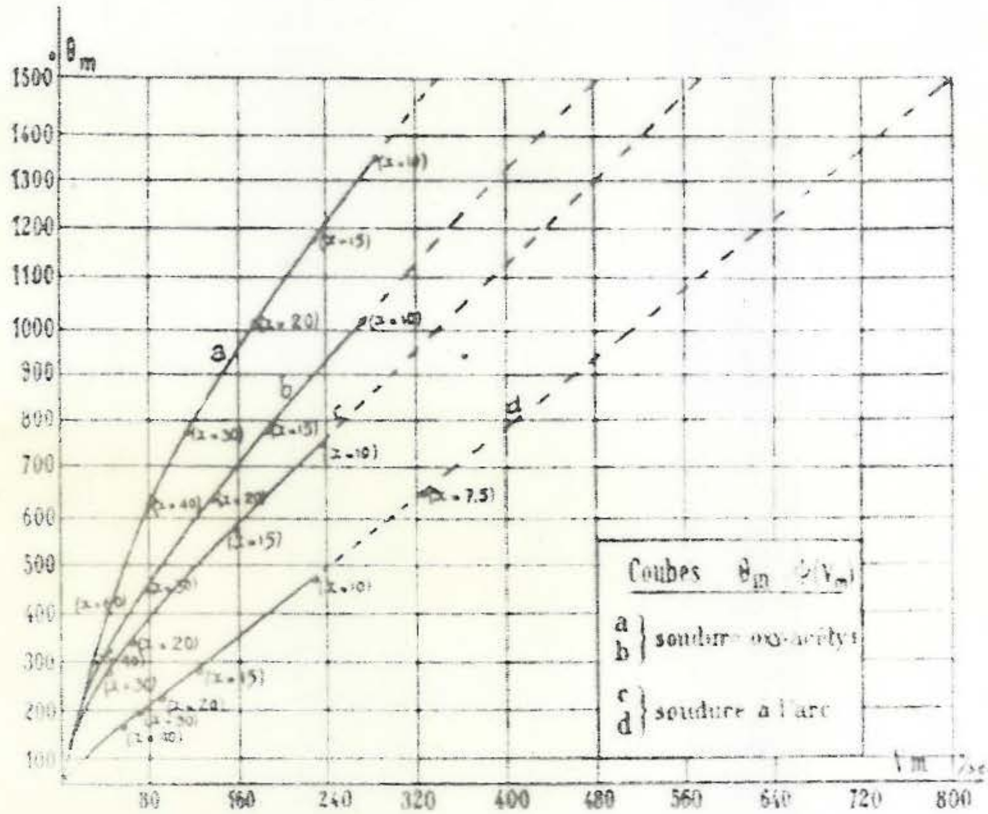

Fig.20 - $\lambda = f(x)$ curves obtained from the thermal surfaces, as a function of maximum temperature and maximum speed of cooling; oxy-acetylene welding of 10 mm. thick plate of steel (a), 10 mm. square steel bar (b); electric arc welding of 10 mm. thick,steel plate (c), 10 mm. square bar (d).