TECHNICAL REPORT

ON

INVESTIGATIONS OF BRITTLE CLEAVAGE FRACTURE OF WELDED FLAT PLATE BY MEANS OF A BEND TEST

BY

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University of California
Under Bureau of Ships Contract NObs-31222

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

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Dear Sir:

Attached is Report Serial No. SSC-6 entitled "Investigation of Brittle Cleavage Fracture of Welded Flat Plate by Means of a Bend Test." This report has been submitted by the contractor as a technical report on one phase of the work done on Research Project SR-92 under Contract NObs-31222 between the Bureau of Ships, Navy Department and the University of California.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Construction, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

Frederick M. Feiker

Frederick M. Feiker, Chairman
Division of Engineering and
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Enclosure

PREFACE

The Ship Structure Committee through the Bureau of Ships is distributing this report to those agencies and individuals who were actively associated with this research program. This report represents a part of the research work contracted for under the section of the Committee's directive to "disseminate pertinent information to all parties having an interest in the building and operating of ships.

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ABSTRACT

Reported herein are the results of several series of bend tests conducted on 10-in. square by 3/4-in. thick plates upon which had been deposited weld metal. The experiments were carried out in conjunction with tests on large welded tubes of ship plate. The work was begun as part of NDRC Project NRC-75 and completed under U. S. Navy Contract NObs-31222.

This report presents a description of the test specimens and the testing technique. Both double-V butt-welded and single-bead specimens were tested as simple beams supported on a 6-in. span, centrally loaded. The weld or bead was so placed that it was stressed in tension by the applied load. Tests were made at various temperatures ranging from room temperature to -40°F on specimens welded with E6010 electrodes, low-alloy steel electrodes, 25-20 stainless steel electrodes, and with Unionmelt. The effects on ductility at -40°F of preheating to various temperatures ranging from 0°F to 500°F, of postheating to 1100°F, and of normalizing were determined. The effect of arc voltage and the effect of the weld contour on the ductility at various temperatures were determined for E6010 and Unionmelt deposits. Chemical analyses of typical weld deposits were made and the microstructure of most of the specimens was studied, and microhardness surveys were conducted on about half of the specimens tested. Included in the report are the following data: welding conditions, testing temperature, bend angle, maximum elongation, maximum load and type of failure, microstructures, and hardness values.

The cracks were found to originate in the weld metal and not in the heat-affected zone of the base plate even though the heat-affected zone

was in many cases much harder than the weld metal. The ductility of the bend test specimens was found to be improved by preheating, postheating, low arc-voltage and by the use of stainless steel electrodes. The ductility was decreased by low preheat temperature, low testing temperature, fast rate of electrode travel, high arc voltage, and by the use of electrodes having high hardenability.

Technical Report

U.S. Navy Research Project NObs-31222
(Causes of Cleavage Fracture in Ship Plate)

on

INVESTIGATION OF BRITTLE CLEAVAGE FRACTURE OF WELDED FLAT PLATE BY MEANS OF A BEND TEST

May 1946

From: University of California, Berkeley, California
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Introduction

The work reported herein was conducted under OSRD Contract OEMsr #1418 and U.S. Navy Contract No. NObs-31222, which became effective August 31, 1945.

The formally stated purposes of the general investigation are: (1) determinations of the behavior of steel under conditions of multiaxial stress, (2) determination of factors responsible for the brittle cleavage fracture of ship plates without manifestation of appreciable ductility or plastic flow. The experimental work was divided into two main sections: (a) investigations of the effects of stress and temperature conditions on the tendency of various steels to fail in a brittle manner, in which the principal tests are made on test specimens in the form of tubes and flat plate, and (b) investigations of the behavior of built-up weldments, principally in the form of sections made to simulate welded hatch corners, to study the influence of design as well as of materials on behavior under load. The subject of this report is concerned with some special studies made in conjunction with section A of the general investigation.

In the course of the investigation on large welded tubular specimens subjected to various conditions of bi-axial stress, a number of questions were raised as to the effect of metallurgical changes caused by the welding process on the mode of failure. In an attempt to interpret some of the results of the tests on the large tubes, some bend tests were made on samples taken from the welded portions of certain of these tubes. The apparent successful correlation of the results of these simple bend tests, as regards certain conditions of failure, led to an amplification of the study to cover the effect of various weld conditions on the mode of failure.

Owing to the lack of success in previous attempts to explain causes of failure of weldments by means of standard tensile and impact tests on small specimens taken from a weldment, it was considered desirable to utilize a test specimen and a procedure where the interaction of the weld metal and parent metal would be closely similar to that existing in an actual structure or part. Furthermore, since metallurgical examinations have shown that a gradation in metallurgical structure may take place within very short distances in certain zones, a test which would include the effect of the anisotropy seemed preferable.

Because questions raised by the experiments on the large welded tubes are the reason for undertaking the bend tests, and because the tube experiments form a general background for interpreting the bend test studies, the principal and pertinent results of the tests on the tubular specimens are summarized in the following paragraphs.*

<u>Summary of Results of Welded-Tube Tests.</u> -- The 20-inch diameter tubular specimens were made by forming two pieces of 3/4-inch thick ship plate into half-cylinders each 10 feet long. These pieces were then welded together by two longitudinal seams 180° apart to form cylinders. The chemical composition of the steel used for the cylinders, designated as Steel A, is given in Table 1. E6020 electrodes were used for the welding. Ten tubes were tested, two of which were heated 6 to 8 hours at 1100°F. after welding ("post-heated"). The remaining 8 tubes were given no heat treatment after welding. Tests were conducted at 70°F and -40°F, using various ratios of longitudinal to transverse stress.

The results of the tests are summarized in Table 2. All the tubes tested at 70°F exhibited considerable ductility prior to fracture. All the tubes tested at -40°F except those post-heated to 1100°F, were relatively brittle. The reduction in wall thickness of the tubes tested at -40°F ranged from 2 percent to 6.7 percent for the tubes tested as welded, while the post-heated tube had a wall-thickness reduction of 31 percent before failure. The tubes tested at 70°F were more ductile. Reductions in thickness ranged from 7.5 percent to 32 percent.

A study of the fractures revealed that the origins of the fractures were almost invariably in the welds even though the welds were sound. The welds appeared to be acting as crack starters thus causing premature failures of the tubes. In view of the nature of the failures obtained with the tubes, it was considered advisable to conduct some supplementary tests on the weld deposit of the

*H. E. Davis, G. E. Troxell, E. R. Parker and M. P. O'Brien, "Behavior of Steel Under Multi-Axial Stresses and Effect of Welding and Temperature on This Behavior". Ship Plate Series (NS306), OSRD Report 6365, Serial M-542, Dec. 6, 1945.

tubes. This was possible because two 8 in. lengths had been cut from the ends of each cylinder in preparation for testing. From these rings were machined standard 0.505-inch tensile test bars.

Tensile tests were made at 70 and -40°F on specimens cut from the tube walls and from the welds. Typical true-stress natural-strain curves of these materials are given in Figure 1. Both the weld material and the plate material were very ductile. Contrary to the behavior of the tubes, the tensile specimens showed greater ductility at -40°F than at 70°F. This apparently inconsistent result might be due to one of a number of causes. The 0.505 inch diameter tensile bars were cut from the center portion of the weld; thus the last passes deposited at the surfaces of the welds were not tested. It is the surface layers in the multipass weld which are likely to be the least ductile. All underlying passes are reheated by subsequent passes with a consequent improvement in ductility. The surface layers in the weld deposit might be the source of the cracks in the tubular specimens. Another factor which must be considered in relation to the discrepancy between the results of the tensile bars and those of the tubes is the difference in the stress conditions. The tubular specimens were subjected to biaxial loading while the tensile bars were loaded in simple tension. Furthermore, in the tubes the stress condition was complicated by the rough surface of the weld so that triaxial tensile stresses may have existed near local irregularities. This difference in the state of stress presumably might account for the difference in behavior of the material in the two tests. The picture was further complicated by the fact that the weld zone in the tubular specimens had a residual tensile stress estimated to be about 45,000 psi. No residual stress was present in the 0.505-inch diameter tensile bar.

It became apparent that there were many variables which should be evaluated before a critical analysis of the tube test results could be made. The evaluation of the separate factors by menas of the tube tests was considered impractical because of the cost and because of the time necessary for such a study. To facilitate the investigation, a bend test was chosen and used for the studies.

Considerations in Choice of Test. -- Considerable thought was given to the problem of choice of an appropriate test, and a number of preliminary experiments (including some on other types of tests) were conducted to study the merits of various conditions of test. The criteria by which the various possible test procedures were judged were as follows:

1. The outer layer of the weld deposit should be included in the strained material.
2. The specimen must be of such a nature that biaxial stresses can be applied.
3. The specimen must be capable of retaining residual stresses of a magnitude comparable with those in the tubular specimens (18 inch long specimens were used for determining effect of stress).
4. The specimen must be relatively cheap, simple to make and easy to test.

The bend test seemed to satisfy these conditions. The outer layer of the weld undergoes the maximum strain; when wide specimens are bent as simple beams there is developed a transverse stress equal to one-half of the longitudinal stress (a stress ratio of 1:1 is produced in a cupping test); bend test specimens can be made large enough to retain large residual stresses (18" long or more); the cost of making and testing such specimens is relatively small.

Although the bend test seemed ideally suited for the proposed experiments, its suitability needed to be evaluated experimentally. This was done by making bend tests on specimens cut from the tubes. The specimens contained the weld zone and about three inches of the adjacent plate material. The results obtained with these bend test specimens correlated very well with the results of the tube tests. (Details are given later in report under Experimental Results). Consequently, the bend test was adopted for evaluating the influence of the various factors.

Testing Procedure

All bend test specimens used in the experimental work (except those cut from Tube I and J) were 10 in. square by 3/4 inch thick.

Most of the specimens were made by depositing beads along the center line of one face and parallel to the direction of rolling of the plate. Some of these specimens were subsequently tested in the as-welded condition, i.e. with the beads not ground off, while others were tested after the beads had been ground flush with the surface of the plate. Additional bend tests were made on specimens of the same size but containing double-V butt welds instead of single beads. The butt-welded specimens were made by welding together two 5-in. by 50-in. pieces of 3/4-in. thick plates. The long welded pieces were then cut into 10-in. lengths to form the square bend-test specimens.

In some series of experiments, the plates were heated or cooled to various temperatures before the beads were deposited. The heating was done with an acetylene torch and the temperature of the plate was measured by a contact pyrometer. The temperature of the plate just ahead of the arc was maintained within ten degrees of the desired temperature during the welding. Some of these specimens were subsequently post-heated in controlled temperature muffle furnaces to determine the effect of post-heating upon the ductility.

All specimens were loaded as simple beams on a 6-in. span so that the direction of the maximum tensile stress was parallel to the bead or to the butt weld. The supports extended across the entire width of the specimen. The load was applied at the midspan through a loading member which also extended across the entire width of the specimen. The loading member was rounded to a radius of 1/4 inch on the edge where it contacted the test specimen. The fixtures which supported the ends of the beams were also rounded to a 1/4 inch radius and were recessed to accomodate the weld bead so that the plate rested on the supports across the entire width.

Tests were conducted at various temperatures ranging from room temperature (about 70°F) down to -40°F. The specimens were cooled with dry ice to a temperature slightly below the desired testing temperature. A specimen was placed in the testing jig and the test was begun when the temperature (measured with a thermocouple attached to the surface of the plate) reached the value recorded in the tables of test results. The specimens were loaded as rapidly as possible to maximum load. The loading operation required from 15 to 30 seconds depending upon the ductility of the specimen. Because of the rapid loading, the tests were adiabatic rather than isothermal. The temperature rise which occurred during the test varied from a few degrees for the brittle specimens to as much as 25°F. for the most ductile specimens. Since the results of the tests are comparative, only the temperatures of the plates at the start of the tests are reported.

During the course of preparation of the specimens, measurements of the plate temperature were made prior to welding, and the welding currents, voltages and rate of electrode travel were recorded. During each test, the temperature, maximum load, bend angle and surface elongation were measured. The elongation was measured parallel to the weld over a one-inch gage length and in the region of maximum elongation. Unfortunately, it was impossible to observe the action of the weld during the test so no record of when the first crack formed is available. Most of the specimens tested at low temperatures fractured completely across the plate when the first crack formed. At room temperature, however, the weld zone usually cracked in several places and often the plate did not fracture. In such cases, the cracks formed at bend angles which were sometimes much smaller than those recorded in the tables. The bend angles at the high temperatures thus measured the ductility of the plate material rather than the ductility of the weld deposit. The low temperature tests, however, provided a better measure of the weld zone ductility because the first crack which formed caused the plate to fracture without additional deformation.

Experimental Results

The studies conducted during the course of the investigation may conveniently be divided into ten groups, as listed below.

1. Bend tests on samples cut from tubes.
2. Experiments with E6010 electrodes.
3. Experiments with Unionmelt.
4. Experiments with low-alloy electrodes.
5. Experiments with stainless steel electrodes.
6. Effect of composition and microstructure of the base plate.
7. Effect of pre-heating and post-heating.
8. Evaluation of the effect of residual stress (with 18" long specimens).
9. Effect of arc voltage.
10. Evaluation of the metallurgical factors.

The results will be discussed in the order listed.

1. Bend tests on samples cut from tubes. The first step in conducting the experiments was to determine the suitability of the bend test as an indicator of the performance of welded structures such as the pressure vessels studied on NDRC Research Project NRC 75. Whether or not the bend test would yield brittle and ductile fractures to correspond with the fractures obtained with tubes was an importent factor to be determined.

As described in the introduction, the tubular specimens were tested under various ratios of longitudinal to transverse stress; hence the biaxial stress ratio of 2:1 developed on the tension side of the bend test specimens was the same as that used for some of the tubes. The temperature of the bend test was also adjusted to correspond to that used in the tube tests. The bend test thus satisfied the conditions of stress and temperature.

During the preparation of the tubes, sections about 8 inches long had been cut from each tube. From some of these sections, pieces about 8 inches square were cut which contained the welds. These rather crude specimens were then bent in such a way that the longitudinal weld was stressed in tension, similar to the manner in which their counterparts in the tubes were stressed. The specimens were tested as centrally-loaded beams on a 6 inch span. The curvature of these specimens, though slight, made a quantitative interpretation of the results complicated but the difference between the ductile and the brittle specimens was so obvious that refinements were not necessary. Furthermore, the behavior of the specimens in the bend test corresponded with the behavior of the tubes from which the bend test specimens were cut. Figure 2 shows the results obtained when two of the specimens were bent. The ductile specimen was taken from Tube I which had been post-heated to 1100°F after welding; the brittle specimen was taken from Tube J which was left in the as-welded condition.

It appeared from these preliminary results that the bend test might afford a quick, economical and satisfactory means for evaluating some of the many complex factors which seemed to influence the behavior of loaded welded joints. With this belief in mind, the following experiments were performed.

2. Experiments with E6010 Electrodes. One of the electrodes commonly used for the welding of mild steel is the E6010 type of electrode. This electrode is made of low carbon steel and has a cellulose coating. A Fleetweld 5 rod was chosen for these tests. All of the bend test samples in this series of tests were 10 inch square and 3/4 inch thick. Most of the specimens were made of single 10 inch square plates on which weld beads were deposited. Some of the specimens,

however, were made of two 5 inch wide, 50 inch long plates joined by a double-V butt weld and subsequently cut to 10 inch squares. Only steel A was used for these experiments with the E6010 electrodes.

The plates were tested as centrally-loaded simply-supported beams with a six inch span. The weld beads were placed in the longitudinal direction so that the maximum tensile stress was parallel with the direction of the weld. The resulting fractures thus traversed the bead. Specimens welded at room temperature were bent at temperatures ranging from 70° to -40°F. The results of these tests are recorded in Table 3 and Figure 3. Figure 3 shows the effect of testing temperature on the bend angle obtained in these tests. These results clearly showed the influence of the testing temperature upon the ductility.

A comparison between the double-V butt-welds shows a striking contrast in behavior. The weld made by a series of longitudinal passes (single pass stringer beads) was extremely brittle while the weld made by oscillating the electrode from side to side so that the entire groove was almost filled in a single pass (wash weld) was very ductile. The difference in welding technique had a profound effect on the ductility of the weld. The specimens were made by welding together two 5 inch wide pieces of plate each 50-in. long. The stringer beads were started at one end of the plate and deposited progressively towards the other end. By the time one pass was completed, the plate at the place where the weld was begun had cooled to room temperature. Thus each pass was deposited on a cold plate and consequently cooled at a rapid rate. The wash weld progressed so slowly, however, that the plate ahead of the weld was actually preheated by heat which diffused forward faster than the weld progressed. The primary difference in behavior appeared to be due to the difference in the rate at which the weld zone cooled. This observation led to another series of experiments recorded as part 7 of this report.

The results from the specimens having a single bead were intermediate between those for the two types of butt welds. The cooling rate of the single bead deposits was, of course, much faster than that of the wash weld. Consequently, it is to be expected that the single bead deposits would be less ductile than the double-V butt welds made by the wash weld technique. The cooling rate of the weld zone in the double V butt welded specimens made by the stringer bead technique must have been of the same order of magnitude as that of the single bead specimens, yet the single bead specimens were more ductile than those that were butt-welded. The difference in ductility is apparently due to the difference in the contour of the surface. The single beads were ground flush with the plate surface while the butt-welded specimens were not ground. This conclusion was confirmed by later tests on single bead specimens tested in two conditions--as welded and with the beads ground flush (see Fig. 8).

3. Experiments with Unionmelt and Steel A. Unionmelt welding is commonly employed for the welding of flat mild steel plate. Hence it was considered desirable to study the performance of Unionmelt welds. In this series of experiments, single beads were deposited at high rates of speed to obtain deposits as nearly comparable with those deposited by hand with the E6010 electrodes. A current of 320 amperes was used with a 1/4-in. rod. The rate of travel of the electrode was 15-in. per minute. Thus a small bead was obtained. The beads were deposited at room temperature and the specimens were tested at various temperatures ranging from 70° to -40°F. The results are recorded in Table 4 and the bead angle is plotted as a function of temperature in Fig. 4. The Unionmelt specimens showed

greater ductility than did the specimens having E6010 beads. This can be at least partially accounted for by the fact that, in spite of all that could be done to deposit metal at the same rate in the two cases, the bead deposited by the Unionmelt process was larger and consequently cooled at a slower rate than did the E6010 bead. There are, however, other conditions which were different in the two cases and might presumably influence the results. One of the most important differences was in the arc atmosphere. The atmosphere surrounding the arc made by the E6010 electrode was undoubtedly rich in hydrogen gas originating from the cellulose coating on the electrode. The Unionmelt flux, on the other hand, is a mineral type coating containing silicates of calcium, aluminum, etc. and consequently generated little hydrogen when it was fused. It is well known that excess hydrogen lowers the ductility of alloy steel welds, and it may be that hydrogen has a similar effect on low carbon steel.

Double-V butt-welded specimens were also made by the Unionmelt process using standard welding procedure. The 10-in. square specimens were cut from a long piece made by welding together two 5-in. wide pieces of plate each 50-in. long. The weld was started at one end and progressed continuously towards the other end. One pass was deposited on each side of the plate. The last side welded was placed in the bending jig so that it would be stressed in tension during the test. Tests were made on these specimens at various temperatures. The results are reported in Table 4 and the bend angle is plotted as a function of the temperature in Fig. 4.

The single-bead specimens were more ductile than the butt-welded specimens even though the single-bead deposits cooled more rapidly than the butt welds. The difference in ductility was undoubtedly due to the surface condition. The single bead specimens were ground flush with the surface of the plate while the butt welds were not.

4. Experiments with Low-alloy Electrodes and Steel A. Another series of experiments was conducted with several types of low-alloy steel electrodes--Shield-arc 85, Murex Type 80 and Murex AWL. It must be recognized at the outset that bead tests with alloy steel electrodes are likely to be misleading. The alloy steel electrode is diluted excessively by the mild steel in a single bead deposit. Consequently, it is necessary to know the actual composition of the weld deposit before the results of the bend test can be intelligently appraised. To obtain this information, metal was machined from the central portion of the beads of some of the specimens after they were tested. These chips were then analysed along with similar samples obtained from other specimens. The chemical compositions are reported in Table 5. The results of the bend tests are given in Table 6 and the bend angle is plotted as a function of testing temperature in Fig. 5. The bend angles of the specimens made with the Murex Type 80 electrode were essentially independent of the testing temperature while the bend angles of the specimens made with the AWL electrodes were roughly the same as those obtained with E6010 specimens. The specimens welded with Shieldarc 85 were the most brittle specimens tested. The hardnesses of the beads and heat-affected zones in these specimens were later measured with a microhardness tester. The results obtained are discussed in detail in section 10 of this report.

5. Experiments with Stainless-Steel Electrodes and Steel A. Experiments were made with columbium-stabilized, 19 percent chromium, 9 percent nickel electrodes, and with 25 percent chromium, 20 percent nickel electrodes. The beads

made with the 19-9 electrodes were so brittle that even at room temperature many cracks developed in the weld deposit when the specimens were bent through very small angles. The 19-9 electrode material was so diluted during welding that the single bead deposited on the plate had a very poor metallurgical structure. To avoid this condition, 25-20 electrodes were used thereafter. Even with this electrode the weld deposit was diluted by the fused base material but not enough to cause the formation of the brittle metallurgical structure associated with the 19-9 deposit. The composition of the 25-20 beads is given in Table 5.

The results of the bend tests obtained with 25-20 beads are given in Table 6 and the bend angles at various temperatures are plotted in Fig. 5, together with the results from tests on specimens having low-alloy steel beads. It is important to note that no cracks formed either in the weld zone or the plate at any testing temperature.

A microscopic examination was made of the weld zone to determine whether or not the heat-affected zone of the plate had cracked. Microcracks could conceivably form in this zone but might not grow. Microhardness surveys later revealed that this zone had a maximum hardness of about 500 Knoop which is equal to approximately 500 Brinell. A careful microscopic survey of the hardened zone failed to show any cracks. This seemed remarkable considering the hardness of this material.

The 25-20 type of welding electrode seemed to be ideal for the welding of mild steel to prevent low temperature brittleness in the weld zone. The reason for the remarkable performance of the 25-20 specimens was not immediately apparent. Two factors might contribute to the favorable action of this electrode.

One is the good ductility and insensitivity to notches of the weld bead; the other is the low hydrogen content of the arc atmosphere. The 25-20 electrodes had a lime-type coating which liberated relatively little hydrogen. The results obtained on mild steel with this type of electrode are in line with those reportedly obtained with the same type of electrode on low-alloy steel.

A word of warning is necessary, however, in connection with the use of 25-20 electrodes for the welding of mild steel. Some later experiments were performed which indicate that the results obtained in the original tests must be reconsidered. In the final experiments several identically prepared bend test specimens were tested in bending with the bead running transversely rather than longitudinally. The heat-affected zone of the plate was thus subjected to the maximum tensile stress over the entire length of the bead. The bead was left on the specimens and consequently acted to concentrate stress at the junction of the bead and the plate where the heat-affected zone is located. These specimens, when tested at -40°F., fractured through the heat-affected zone after bending through a relatively small angle. These results show that the use of 25-20 electrodes for welding mild steel will not always prevent brittle fractures from starting in the weld zone, and that the state of stress and the orientation of the principal stresses is a factor in determining the ductility and failure, especially when marked variation in hardness exists in the weld zone.

6. Effect of Composition and Microstructure of Base Plate. Some limited experiments were performed to explore the effect of composition and microstructure of the plate metal on ductility of weldments. Semi-killed steels of two different compositions (steels A and B) were used for these bend tests. One of these steels was tested in two different conditions of heat treatment (B as

rolled, and B normalized). The compositions and heat treatments of these steels are given in Table 1. Unionmelt weld beads were deposited on specimens of these plates. The results of the bend tests are recorded in Table 7 and the bend angles at various temperatures are plotted in Fig. 6. As indicated by the difference between the behavior of steels A and B, the chemical composition has some effect, although it was apparently small in this case. More important is the fact that the B steels, which were chemically identical, behaved differently in the two different conditions of heat treatment. There was a small difference in microstructure which can be seen in the photomicrographs shown in Fig. 7. The microstructure of steel A is given for comparison. The difference in the results obtained with the two B series of specimens makes it obvious that microstructure of the base plate must be considered as an important factor. It is not sufficient to study the effect of chemical composition alone. A study of the effect of chemical composition and microstructure is in itself a major project so it was not considered advisable to extend the study at this time.

Cracks which developed first in the weld metal in this group of test specimens apparently acted as notches so that the behavior of the plates (after the welds cracked) was conditioned by the notch sensitivity of the base metal.

7. Effect of Preheating and Postheating. A number of experiments were performed to determine the effect of preheating and postheating on the behavior of bend test specimens. The plates were cooled or heated to various temperatures as indicated in Table 8 before the weld beads were deposited. The bend angles obtained for tests at -40°F plotted against the preheat temperature for specimens with E6010 beads are shown in Fig. 8. Specimens were tested both with the beads left on and with the beads ground flush with the surface of the plate.

The specimens tested in the as-welded condition (beads not ground) were considerably more brittle at the low temperatures than were the specimens for which the beads were ground flush. It is important to note, however, that even the as-welded specimens were extremely ductile if the weld beads were deposited on hot plates. The bead contour had no effect upon the bend angle when the plate was heated above 400°F before welding. The remarkable effect of preheating upon the ductility of the bend test specimens was found to be true for all types of electrodes used and is undoubtedly the result of the slower cooling associated with the preheating. Slower cooling causes a softer microstructure to result and also allows more time for dissolved gases, particularly hydrogen, to escape. Additional comment is given in section 10 concerning the effect of preheating on the microstructure of the weld zone.

Fig. 9 shows the effect of preheating upon the bend angle at -40°F for specimens having various kinds of weld beads.

For some specimens, the plates were at 100°F before welding, and subsequent to welding were heated to 1100°F for one hour. As shown in Table 8 and in Fig. 10, this treatment had a pronounced effect upon the ductility of the bend test specimens tested at -40°F. Similar specimens were given a normalizing treatment (heated to 1650°F and air cooled) which, in general, seemed to yield results similar to the treatment at 1100°F. The results of some of the tests on normalized specimens are also reported in Table 8 and are plotted in Fig. 10.

The beneficial effect of postheating is obvious. The reason for the improvement is not clearly brought out by the tests. The 1100°F treatment is generally called a stress-relief heat treatment and it is true that it does relieve the residual welding stresses to a large degree. One important question is whether or not the relief of the residual stress is responsible for the remarkable improvement in the performance of the bend test specimens (and for the improvement in the ductility in the large tubular specimens). To establish the role played by residual stress, another series of experiments was conducted which are described in detail in the following section.

8. Evaluation of the Effect of Residual Stress. Although weldments which are given the so-called stress-relief heat treatment are largely relieved of residual stress, a microscopic examination reveals that metallurgical changes have also occurred in the heated specimens. (The details of the metallurgical changes are discussed in section 10.) Consequently, it was considered necessary to evaluate the effect of stress and the effect of other changes separately. Fortunately this could be done in a simple manner but 18" long specimens had to be used instead of the 10" square type. It had been previously demonstrated* that when all elements parallel to a weld are elongated an amount of about one percent or more, the residual stresses are reduced to a low order of magnitude. Hence by elongating the test specimens about one percent in a tensile testing machine prior to bending, it was possible to eliminate practically all of the residual stress without affecting the metallurgical structure. When this was done, the specimens were tested and found to behave essentially the same as those containing the residual stresses. At -40°F there was a small but perceptibly larger bend angle for the pre-stretched specimens but the difference was very small. The bend angle in all cases was relatively large so that the residual stress could not be expected to show a large effect.

In truly brittle failures where the total elongation prior to failure is only a fraction of a percent, the strain associated with the residual stress would be an appreciable part of the total strain, and residual stresses would be expected to contribute greatly to the fracture. Brittle fractures of this

*E. P. DeGarmo, J. L. Meriam and Finn Jonassen: "Residual Stresses in Ship Welding (NS-304)", OSRD Report No. 4388, Serial No. M-370, Nov. 13, 1944.

nature were not obtained within the range of temperature employed in these tests, and consequently the residual stresses could not have played an important role in the bend test results. This conclusion was checked in several ways.

It was also found that residual stresses of high magnitude could be induced in bend test specimens by local heating with an acetylene torch. The maximum temperature was never allowed to exceed 500°F so no metallurgical changes could occur in the mild steel plates. These specimens thus had the residual stresses but had no discontinuity in the metallurgical structure as did the welded specimens. In the bend tests, there was no difference in behavior between the plates with residual stress and those without.

Still another check was made on the effect of residual stress. The specimens preheated to 500°F were found to have a residual stress pattern almost identical with the stress pattern in the specimens welded without preheat. The preheated specimens thus had the residual stress but had very different metallurgical structures. The preheated specimens were very ductile compared with those specimens not preheated.

The conclusions reached were: (1) residual stresses have little influence on the ductility of bend test specimens tested, (2) the beneficial effect of the so-called stress relief heat treatment is primarily the result of changes in the metallurgical structure (which may include the elimination of hydrogen which apparently causes brittleness when present in large amounts in the weld zone).

9. Effect of arc voltage. It was observed by H. E. Kennedy* that welds made at high voltages tend to be brittle in the bend test. Some experiments were conducted to check his observations. The results of the investigation are summarized in Table 9 and the bend angle vs. temperature curves are plotted in

*H. E. Kennedy, "Some Causes of Brittle Failures in Welded Mild Steel Structures," Welding Journal, Nov. 1945, Welding Research Supplement, p. 588s.

Fig. 11. It should be noted that preheating relieves the brittleness induced in the weld zone by the high welding voltage. The mechanism by which high welding voltage influences the ductility of the weld is not clear. It is conceivable that the silicon content of the Unionmelt weld is increased by the high voltage. This would account for the increased brittleness of the Unionmelt weld but not for that of the hand weld. The increased brittleness of the specimens made with the Fleetweld 5 rod might be explained by the increase in the nitrogen and hydrogen contents which presumably result from the high voltage welding. No single explanation seems adequate at the present time and it is possible that several factors contribute to the brittleness of the specimens welded at high voltage.

10. Evaluation of metallurgical factors. The most striking results in the bend test experiments were those obtained by preheating and postheating. The effects were obviously not related to the residual stresses but appeared to be closely associated with the metallurgical structure of the weld and heat-affected zone. Microhardness surveys were made of a number of the bend test specimens to determine the relative hardnesses of the weld zones. The results of these surveys are given in Appendix A along with macrographs showing the contours of the weld beads (which are also important in determining the performance of bend test specimens).

The results of these hardness surveys may be generalized briefly as follows: the higher the preheating temperature the softer the weld zone; postheating at 1100°F softened the weld zone; the hardness was a maximum in the heat-affected zone. The heat-affected zone required special study because of the high hardnesses found there. (In some cases the hardness exceeded 450 Knoop which is roughly equal to 450 Brinell). The structure was not martensitic but appeared to be Bainitic. The heat-affected zone is heated above the transformation temperature during the welding and subsequently cools to room temperature. The cooling is unusual in this zone, however, because it is first cooled very rapidly by the cold plate near the weld but the cooling rate is rapidly slowed down as the base plate becomes heated until the cooling becomes extremely slow as room temperature is approached. This type of cooling is conducive to the formation of Bainite which seemed to be the structure in the heat-affected zone. The high hardness in this zone indicated that this region was the most likely place for cracks to originate. This conclusion did not agree, however, with the observations reported for the bend test specimens having 25 Cr - 20 Ni beads which were very ductile and did not crack in the heat-affected zone even though the maximum hardness in this region was about 500 Knoop.

Many of the bend test specimens having plain carbon and alloy steel beads were also examined microscopically to determine the origin of the cracks. In almost every case, the cracks started in the weld metal. A photograph of cracks in various stages of growth is shown in Fig. 12. A few cracks were found to start in the heat-affected zone of some of the specimens examined but such cracks were exceptional. It immediately became obvious that the properties of the weld metal were the important factors governing the behavior of the bend test specimens. It appears, then, that preheating and postheating improve the ductility of the bend test specimens because of the effect of these treatments on the properties of the weld deposit. It should not be assumed, however, that the heat-affected zone is never a source of trouble, because in several cases cracks were observed to start in this region. The 25-20 specimens bent with the beads transverse to the beam axis cracked in the heat-affected zone after only moderate amounts of strain had occurred.

CONCLUSIONS

1. Bend test specimens made by depositing weld metal of various compositions on mild steel plate became progressively more brittle as the testing temperature was lowered.

2. Differences in welding technique made a large difference in the ductility of mild steel welds. Double-V butt welds made with E6010 electrodes using the stringer-bead technique bent through an angle of only 15° when tested at -40°F while similar specimens made by the wash-weld technique bent through 70° to 80°. The difference in the ductility is attributed to the difference in the cooling rates associated with the different welding practices.

3. The cooling rate of the weld appears to be one of the most important single factors in determining the ductility of mild-steel bent-test specimens. The weld zones in specimens preheated to retard the cooling rate were found to be much softer (on the Knoop microhardness scale) than similar regions in specimens which cooled at more rapid rates.

4. Reheating to 1100°F after welding produced changes in the properties and metallurgical structure of the weld zone which changes were very beneficial. However, when tested at -40°F, specimens which had been preheated to 500°F were found to be as ductile as specimens which had been postheated at 1100°F. A complete normalizing treatment (air cooled from 1650°F) did not increase the ductility appreciably more than did the 1100°F treatment.

5. The beneficial effect of preheating could not be attributed to the effect of residual stress because the preheated specimens had essentially the same residual stress pattern as had the specimens welded without preheat. The increase in the ductility could be the result of the difference in the properties as reflected by the microstructure or to a difference in the gas content of the weld zone.

6. The so-called stress-relief heat treatment (1100°F after welding) produced beneficial changes in the properties of the weld zone which could not be attributed to the relief of stress. This was demonstrated by stress relieving specimens by stretching prior to bending (stress relieving by stretching does not change the metallurgical structure) and by introducing residual stresses in an unwelded plate by local heating to below 500°F prior to bending. The specimens which were stress relieved by stretching behaved identically with those containing residual stresses. The specimens containing the residual stresses, but having no weld, behaved exactly like similar specimens having no residual stress.

7. The heat-affected zone of the base plate was found to have a maximum hardness which in some cases exceeded 450 Knoop (approximately 450 Brinell). This zone appeared to have a Bainitic type of microstructure.

8. Microscopic observations established that cracks originated in the weld metal and not in the heat-affected zone even though the heat-affected zone was usually harder than the adjacent weld metal.

9. Specimens made with 25 percent CR, 20 percent Ni electrodes were found to be very ductile when tested at low temperatures, even when welded without preheating of the base plate.

10. High arc voltages were found to produce less ductile welds than lower arc voltages.

APPENDIX A - RESULTS OF MICROHARDNESS SURVEYS

Cross-sections of a number of typical specimens on which weld beads had been deposited were prepared for microscopic examination and hardness testing. Hardness was measured along a line through the center of the weld beads, across the thickness of the plate, starting at the top of the beads. The hardness values were determined as Knoop microhardness numbers and were measured with a Tukon hardness tester which was operated with a 500-gram load in these tests. The specimens were chosen so that comparisons could be made between the effects of preheating, postheating, and chemical composition of weld.

Macrostructures, at a magnification of approximately 4, are shown in the odd-numbered figures, Figs. 13 to 79. The results of microhardness surveys are shown in the even-numbered figures, Figs. 14 to 80; in these latter figures are shown photographic reproductions of the region along which the hardness indentations were made and plots of hardness vs. distance from top of weld bead (top of weld bead as shown in corresponding macrograph). The macrostructures and hardness plots for each specimen are given in consecutive figures so that a comparison can be made between structure and hardness.

TABLE 1. -- COMPOSITION, TREATMENT AND PHYSICAL PROPERTIES OF SEMI-KILLED STEEL PLATES

NOTE: Physical properties based on tests made at room temperature on standard A.S.T.M. 0.505-in. tensile bars, and standard keyhole-notch Charpy specimens, described in A.S.T.M. Specification E8-42.

	Steel A As Rolled	Steel B_{ar} As Rolled	Steel B_n Normalized
Nominal chemical composition	0.25 C 0.47 Mn	0.18 C 0.72 Mn	0.18 C 0.72 Mn
Yield stress, ksi.	35.8	31.9	35.4
Nominal tensile stress, ksi.	58.3	56.7	58.0
Percent elongation in 2 in.	43.5	44.7	45.9
Reduction in area, percent	61.4	69.3	66.7
Energy absorbed in Charpy impact test, ft. - lb.	35.6	48.0	46.7
Hardness, Rockwell "B"	60-62	58-63	59-60

TABLE 2. -- SUMMARY OF TEST RESULTS - 20-IN. DIAMETER TUBES

Specimen	From Plate No.	Stress Ratio,[a] σ_T/σ_L	Loading Conditions	Test Temp. °F.	Conventional Stress psi.[i]		Nominal Stress,[b] psi.		Average True Stress at Fracture,[c] psi.		Maximum Percent Elongation in 5 in.		Reduction in Wall Thickness, %	Potential Energy at Fracture, ft.-lb.[h]	Nature of Fracture
					Longitudinal	Transverse	Prop. Limit	Ultimate	Long.	Trans.	Long.	Trans.			
A	13970	2	Internal Pressure	70	26,250	52,500	30,000	59,000	42,500	<u>85,000</u>	< 1	15.0	30.0	133,000	Initiated by shear in plate about 4 in. from and parallel to weld near mid-section; after shearing for about 5 in., crack propagated over considerable length of tube by cleavage.
H[j]	13991	2	"	70	24,900	49,800	30,000	62,000	45,000	<u>90,000</u>	< 1	21.0	32.0	148,500	Practically same as for tube A.
B[d]	13993	2	"	-42	25,650	51,300	40,000	54,000	30,000[e]	60,000[e]	<0.2	3.0	3.0	110,000	Cleavage fracture entirely around circumferential end weld.
C[d]	13970	1	Axial load, int.press.	70	55,100	51,300	30,000	55,000	<u>60,000[e]</u>	59,500[e]	4.4	4.4	9.0	109,500	Shear for 6 in. (premature);[f] after repair by welding, shear for 4 in., then cleavage.[g]
D[d]	13973 13995	1	"	70	56,800	53,100	30,000	56,500	<u>60,500[e]</u>	56,000[e]	3.5	4.0	7.5	102,000	Cleavage fracture originating in weld about 48 in. from mid-section and propagating spirally around tube.
E	13973	1	"	70	56,800	51,000	30,000	61,500	<u>69,000</u>	72,000	9.2	10.6	20.0	143,000	Cleavage fracture originating in weld 2 in. from mid-section and propagating completely around tube. No shattering.
F	13973 13995	1	"	-44	45,400	44,500	40,000	44,500	<u>45,500</u>	45,500	1.6	2.0	3.5	86,500	Cleavage fracture originating in weld 24 in. from mid-section. Specimen shattered into many pieces.
I[j]	13970	1	"	-39	62,500	51,400	40,000	65,000	<u>85,500</u>	88,500	17.4	18.7	31.0	201,000	Cleavage fracture originating in weld 4 in. from mid-section. Specimen shattered into many pieces.
J	13994	1	"	-38	59,700	59,300	25,000	59,000	<u>61,000</u>	64,500	3.0	3.0	6.7	160,500	Cleavage fracture originating in weld 28 in. from mid-section. Specimen shattered into many pieces.
G	13970	1/2	Axial load, int. press.	-44	50,800	24,700	42,000	49,500	<u>50,000</u>	25,000	2.0	0.3	2.0	38,000	Cleavage fracture originating at defect in plate 90° from weld 44 in. from mid-section and propagating around specimen. No shattering.

a - σ_T = circumferential stress; σ_L = longitudinal stress.

b - Nominal stress computed on basis of original wall thickness but with respect to greatest diameter obtained at the designated load condition.

c - Computed as load on a given section divided by actual cross-sectional area, except as noted in footnote e for specimens failing prematurely. Underlined values indicate direction of stress presumed to govern failure.

d - Failure occurred at or near ends or end connections, presumably due to high complex stresses caused by bending induced by end restraint. However, results are significant in that they indicate average stress levels attained before localized conditions caused failure.

e - Values given are those for mid-section of tube at instant of failure.

f - Shear fracture 6 in. long, crossing longitudinal weld at 1/8 in. from circumferential end weld. Fracture started inside of tube, in circumferential weld.

g - Fracture 4 in. long (apparently shear) at root of circumferential weld, starting about 6 in. from nearest longitudinal weld; then cleavage fracture extending completely around specimen at angle of about 70° from axis.

h - Compression energy in liquid and concrete plugs, and elastic energy in specimen.

i - Computed on basis of original diameter and original thickness.

j - Tube heat-treated for 8 hrs. at 1100°F., after welding.

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TABLE 3. — RESULTS OF BEND TESTS ON 10-IN. SQUARE BY 3/4 IN. THICK PLATES OF STEEL A WELDED WITH 5/32 IN. DIAM. FLEETWELD 5 (E6010) ELECTRODES
Arc Voltage 26-28, Welding Current 150 Amps.

Specimen No.	Type of Weld Material	Rate of Electrode Travel, in. per min.	Test Temp. °F	Max. Load Kips.	Bend Angle, Degrees	Elong. in 1 in. percent	Remarks
1	None	—	-40	90	78	28	No cracks
2	Single bead, ground flush with plate	10	70	85.3	78	24	Cracks in weld only
3	" " " " " "	10	32	80.2	60	19	" " " "
4	" " " " " "	10	0	79.8	59	20	" " " "
5	" " " " " "	10	-20	76.1	33	14	Cracks in weld and plate
6	" " " " " "	10	-40	71.0	24	40	" " " " "
7	Double V butt-weld, stringer beads, cooled to 70°F between passes, as welded	10	70	81.6	55	22	Cracks in weld only
8	ditto	10	32	81.3	42	15	Cracks in weld and plate
9	ditto	10	0	79.3	32	12	" " " " "
10	ditto	10	-20	74.4	19	7	" " " " "
11	ditto	10	-40	70.6	14	6	" " " " "
12	Double V butt-weld, wash weld technique, cooled to 70°F between passes, as welded.	2	75	92.0	82	28	Cracks in weld only
13	ditto	2	32	89.5	82	28	" " " "
14	ditto	2	0	92.0	72	25	" " " "
15	ditto	2	-20	92.0	81	27	" " " "
16	ditto	2	-40	92.6	69	23	Cracks in weld and plate
17	Double V butt-weld, wash weld technique, cooled to approximately 250°F between passes, as welded	2	75	91.0	83	28	Cracks in weld only
18	ditto	2	32	90.5	79	25	" " " "
19	ditto	2	0	92.0	77	27	" " " "
20	ditto	2	-20	92.6	80	27	" " " "
21	ditto	2	-40	95.0	78	27	No cracks

TABLE 4. — SUMMARY OF BEND TEST RESULTS ON 10-IN. SQUARE BY 3/4-IN. THICK PLATES OF STEEL-A

WELDED BY UNIONMELT PROCESS*

Electrode Diameter 1/4 in., Arc Voltage 26-28

Specimen No.	Type of Weld Material	Welding Current, Amps.	Rate of Electrode Travel, in. per min.	Test Temp., °F.	Max. Load kips.	Bend Angle, Degrees	Elong. in 1 in., percent	Remarks
22	Single bead, ground flush with plate	320	15	70	92.0	75.5	23	Cracks in weld only.
23	ditto	320	15	32	81.0	77	24	Cracks in weld only.
24	ditto	320	15	-20	85.5	68	20	Cracks in weld and plate.
25	ditto	320	15	-40	83.0	42	16	Cracks in weld and plate.
26	ditto	320	15	-60	82.5	38	13	Cracks in weld and plate.
27	Double V butt-weld, cooled between passes, as welded	800	12	75	92.1	66	21	Cracks in weld only.
28	ditto	800	12	32	89.5	44	15	Cracks in weld only.
29	ditto	800	12	0	92.6	51	18	Cracks in weld and plate.
30	ditto	800	12	-20	94.8	56	21	Cracks in weld and plate.
31	ditto	800	12	-40	94.0	34	11	Cracks in weld and plate.

* Oxweld 36 rod, Grade 20 flux.

TABLE 5. -- CHEMICAL ANALYSES OF TYPICAL BEAD DEPOSITS

Specimen No.	[a]Electrode Type	Welding Voltage	Percent of Element Shown					
			C	Mn	Si	Mo	Cr	Ni
2	Fleetweld 5	26-28V	0.18	0.46	0.02			
64	"	26-28V	0.17	0.44	0.04			
70	"	26-28V	0.15	0.43	0.10			
100	"	30-32V	0.15	0.45	0.10			
32	Shieldarc 85	26-28V	0.23	0.45	0.11	0.61		
76	" "	26-28V	0.17	0.40	0.11	0.26		
42	AWL	22-24V	0.24	0.58	0.06	0.13		
37	Murex 80	22-24V	0.24	0.49	0.09	0.09		
47	25Cr-20Ni	26-28V	0.18				16.40	14.18
22	Unionmelt on Steel A	26-28V	0.20	0.42	0.43			
25	" " " "	26-28V	0.17	0.44	0.27			
52	" " Steel B_n	26-28V	0.13	0.62	0.37			
56	" " " "	26-28V	0.13	0.61	0.38			
58	" " Steel B_{ar}	26-28V	0.11	0.60	0.32			
62	" " " "	26-28V	0.12	0.54	0.33			
94	"	34-36V	0.13	0.36	0.49			
95	"	34-36V	0.21	0.38	0.52			

[a]See Tables 3, 4, 6, 7, 8, and 9 for details.

TABLE 6. — SUMMARY OF TEST RESULTS ON 10-IN. SQUARE BY 3/4-IN. THICK PLATES OF STEEL-A WITH BEADS OF SHIELDARC 85, MUREX TYPE 80, MUREX A.W.L. AND 25-20 STAINLESS STEEL ELECTRODES

Electrode Diameter 5/32 in., Welding Current 150 Amps., Rate of Electrode Travel 10 in. per min.

Specimen No.	Type of Weld Material	Arc Voltage	Test Temperature °F	Maximum Load, kips.	Bend Angle, Degrees	Elong. in 1 in., percent	Remarks
32	Shieldarc 85 electrode; ground flush with plate	26-28	70	84.0	66	24	Cracks in weld only
33		"	32	78.0	45	16	Cracks in weld only
34	ditto	"	0	66.0	19	9	Cracks in weld and plate
35	ditto	"	-20	55.0	9	7	Cracks in weld and plate
36	ditto	"	-40	59.0	6	1.25	Cracks in weld and plate
37	Murex No. 80, ground flush with plate	22-24	70	80.0	73	23	Cracks in weld only
38		"	32	80.8	70	23	Cracks in weld only
39	ditto	"	0	80.4	59	20	Cracks in weld and plate
40	ditto	"	-20	79.0	73	23	Cracks in weld only
41	ditto	"	-40	83.0	70	23	Cracks in weld and plate
42	Murex A.W.L., ground flush with plate	"	70	84.6	75	23	Cracks in weld only
43		"	32	74.7	38	13	Cracks in weld only
44	ditto	"	0	77.3	49	15	Cracks in weld and plate
45	ditto	"	-20	76.9	43	15	Cracks in weld and plate
46	ditto	"	-40	64.5	19	7	Cracks in weld and plate
47	25 Cr - 20 Ni Electrode; ground flush with plate	26-28	70	85.6	71	20	No cracks
48		"	32	86.9	71	18	No cracks
49	ditto	"	0	87.3	69	26	No cracks
50	ditto	"	-20	89.2	70	22	No cracks
51	ditto	"	-40	88.4	66	20	No cracks

TABLE 7. -- SUMMARY OF TEST RESULTS ON 10-IN. SQUARE BY 3/4-IN. THICK PLATES WITH UNIONMELT BEADS

Electrode Diameter 1/4 in., Arc Voltage 26-28, Welding Current 320 Amps., Rate of Electrode Travel 15 in. per min.

Specimen No.	Type of Weld Material	Test Temperature, °F	Maximum Load, kips.	Bend Angle, Degrees	Elong. in 1 in., percent	Remarks
22	Unionmelt, single bead, ground flush with plate, Steel A	70	92.0	75.5	23	Cracks in weld only.
23		32	81.0	77	24	Cracks in weld only.
24	ditto	-20	85.5	68	20	Cracks in weld and plate.
25	ditto	-40	83.0	42	16	Cracks in weld and plate
26	ditto	-60	82.5	38	13	Cracks in weld and plate.
52	Unionmelt, single bead, ground flush with plate, Steel B_{ar}	70	73.0	76.5	22	Cracks in weld only.
53		32	79.0	66	22	Cracks in weld and plate.
54	ditto	0	79.0	69	21	Cracks in weld and plate.
55	ditto	-20	73.0	38	14	Cracks in weld and plate.
56	ditto	-40	81.5	50.5	16	Cracks in weld and plate.
57	ditto	-60	69.0	37	13	Cracks in weld and plate.
58	Unionmelt, single bead, ground flush with plate, Steel B_n	70	85.0	71	21	Cracks in weld only.
59		32	81.0	78	21	Cracks in weld only.
60	ditto	0	80.0	86	26	No cracks.
61	ditto	-20	84.5	76.5	22	Cracks in weld only.
62	dttto	40	85.0	57	16	Cracks in weld and plate.
63	ditto	-60	87.0	70	20	Cracks in weld and plate.

TABLE 8. — RESULTS OF BEND TESTS ON 10-IN. SQUARE BY 3/4 IN. THICK PLATES OF STEEL-A

SHOWING THE EFFECT OF PREHEATING AND POSTHEATING

Arc Voltage 26-28

Specimen No.	Type of Weld Material	Electrode diam. in.	Welding Current Amps.	Rate of Electrode Travel in. per min.	Test Temp. °F	Plate Temp. before welding, °F.	Temp of Postheat °F.	Max. Load kips.	Bend Angle Degrees	Elong. in 1 in. percent	Failure
64	Fleetweld 5, bead ground off	5/32	150	10	-40	0	None	67.0	28	10	a
65	ditto	"	"	"	"	100	"	81.0	50	20	a
66	ditto	"	"	"	"	200	"	84.0	81	25	b
67	ditto	"	"	"	"	300	"	86.0	79	25	b
68	ditto	"	"	"	"	400	"	81.0	70	24	b
69	ditto	"	"	"	"	500	"	82.3	74	25	b
70	Fleetweld 5, bead left on	"	"	"	"	0	"	60.0	9	7	a
71	ditto	"	"	"	"	100	"	72.0	26	11	a
72	ditto	"	"	"	"	200	"	84.0	49	19	a
73	ditto	"	"	"	"	300	"	88.4	61	21	a
74	ditto	"	"	"	"	400	"	88.0	71	25	a
75	ditto	"	"	"	"	500	"	87.0	72	24	b
76	Shieldarc 85, bead left on	"	"	"	"	0	"	55.0	7	6	a
77	ditto	"	"	"	"	100	"	70.0	24	12	a
78	ditto	"	"	"	"	200	"	87.0	49	19	a
79	ditto	"	"	"	"	300	"	87.0	55	20	a
80	ditto	"	"	"	"	400	"	84.0	57	20	a
81	ditto	"	"	"	"	500	"	88.0	63	22	a
82	Unionmelt, bead left on	1/4	320	15	"	0	"	75.0	30	12	a
83	ditto	"	"	"	"	100	"	82.0	43	15	a
84	ditto	"	"	"	"	200	"	85.0	47	22	a
85	ditto	"	"	"	"	300	"	86.0	67	23	a
86	ditto	"	"	"	"	400	"	88.0	81	24	c
87	ditto	"	"	"	"	500	"	89.0	91	25	c
88	Fleetweld 5, bead left on	5/32	150	10	"	100	d	88.0	93	26	b
89	ditto	"	"	"	"	100	e	90.0	83	23	b
90	Shieldarc 85, bead left on	"	"	"	-77	100	d	88.0	81	26	a
91	ditto	"	"	"	"	100	e	85.0	86	25	b
92	Unionmelt, bead left on	1/4	320	15	"	100	d	85.5	83	28	b
93	ditto	"	"	"	"	100	e	85.5	83	28	b

NOTES: a - Cracks in weld and plate b - No cracks c - Cracks in weld only d - Postheated at 1100°F. A.C. for one hour.
e - Postheated at 1650°F and air-cooled for 3/4 hour.

TABLE 9. — RESULTS OF BEND TESTS ON 10-IN. SQUARE BY 3/4 IN. THICK PLATES OF STEEL-A

SHOWING EFFECT OF WELDING VOLTAGE

Testing Temperature -40°F., No Postheating Treatment

Specimen No.	Type of Weld Material	Electrode diam., in.	Arc Voltage	Welding Current Amps.	Rate of Electrode Travel, in. per min.	Plate Temp. before welding, °F.	Max. Load, kips.	Bend Angle, Degrees	Elong. in 1 in. percent	Remarks
70	Fleetweld 5, bead left on	5/32	26-28	150	10	0	60.0	9	7	Cracks in weld and plate
71	ditto	"	"	"	"	100	72.0	26	11	ditto
72	ditto	"	"	"	"	200	84.0	49	19	ditto
73	ditto	"	"	"	"	300	88.4	61	21	ditto
74	ditto	"	"	"	"	400	88.0	71	25	ditto
75	ditto	"	"	"	"	500	87.0	72	24	No cracks
82	Unionmelt, bead left on	1/4	"	320	15	0	75.0	30	12	Cracks in weld and plate
83	ditto	"	"	"	"	100	82.0	43	15	ditto
84	ditto	"	"	"	"	200	85.0	47	22	ditto
85	ditto	"	"	"	"	300	86.0	67	23	ditto
86	ditto	"	"	"	"	400	88.0	81	24	Cracks in weld only
87	ditto	"	"	"	"	500	89.0	91	25	ditto
94	ditto	"	34-36	"	"	0	67.6	19	7	Cracks in weld and plate
95	ditto	"	"	"	"	100	72.0	23	12	ditto
96	ditto	"	"	"	"	200	80.0	34	15	ditto
97	ditto	"	"	"	"	300	83.0	43	15	ditto
98	ditto	"	"	"	"	400	77.0	33	14	ditto
99	ditto	"	"	"	"	500	86.0	53	20	ditto
100	Fleetweld, 5, bead left on	5/32	30-32	150	10	0	54.0	4	3	Cracks in weld and plate
101	ditto	"	"	"	"	100	60.0	8	6	ditto
102	ditto	"	"	"	"	200	83.0	40	15	ditto
103	ditto	"	"	"	"	300	73.0	28	12	ditto
104	ditto	"	"	"	"	400	85.0	83	26	No cracks

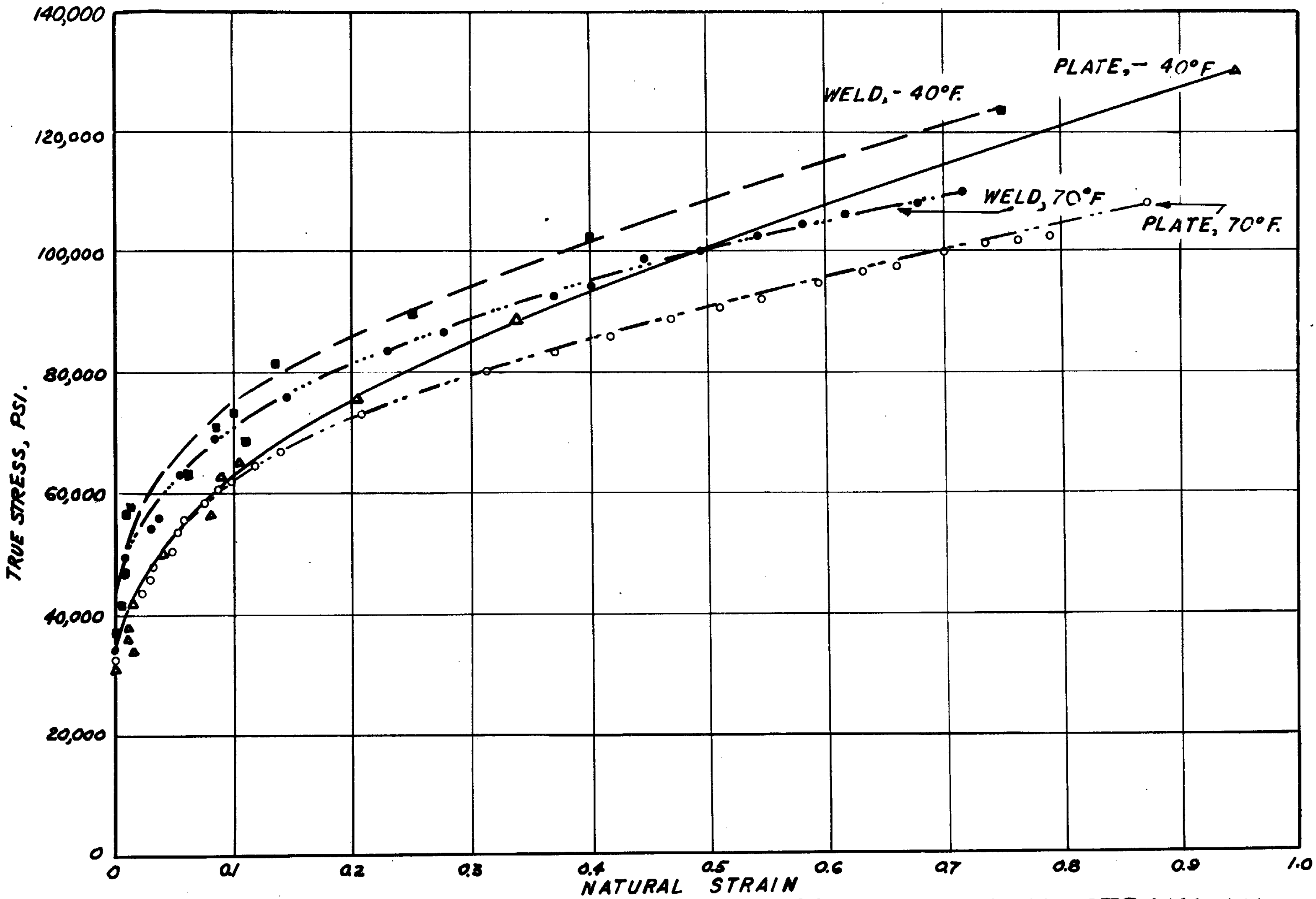


FIG. 1 - RELATIONSHIP BETWEEN TRUE STRESS AND NATURAL STRAIN IN COUPONS CUT FROM WELD AND PLATE OF TUBE J, AT 70°F & - 40°F.

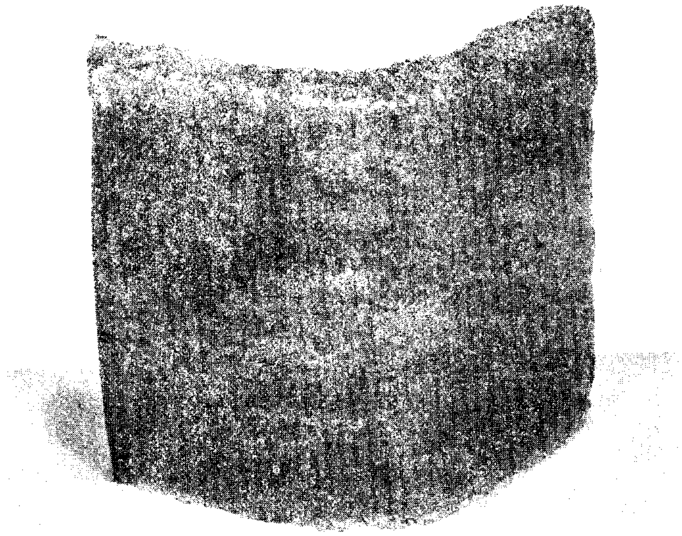


FIG. 2. -- Bend [illegible] from Tubes I and J

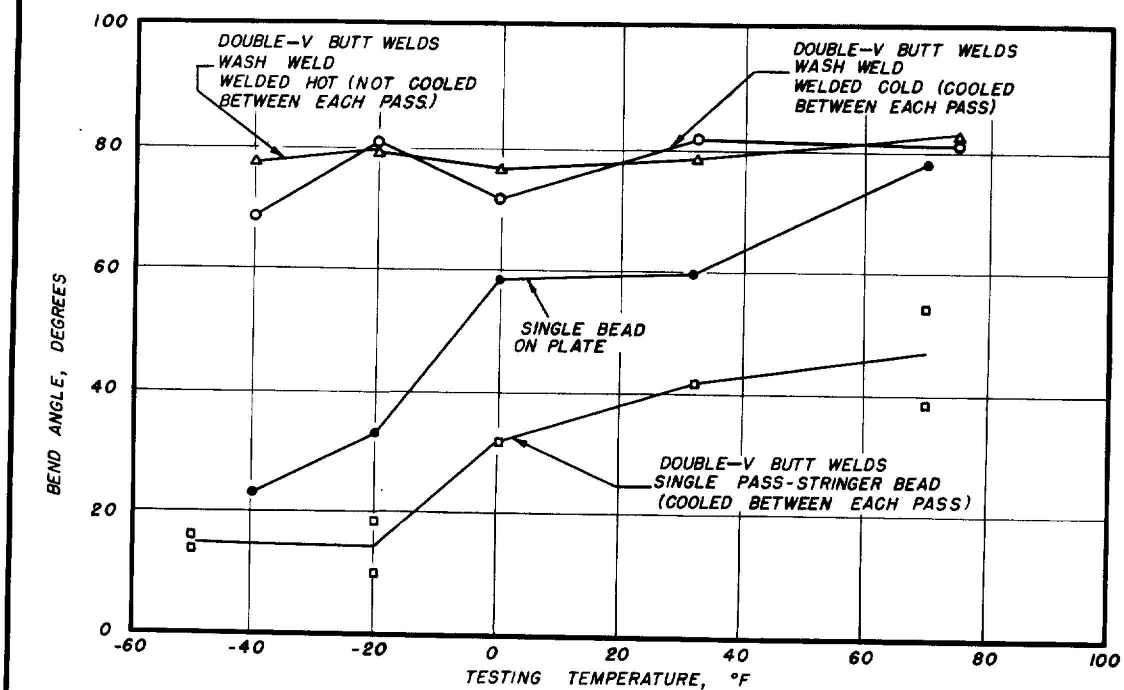


FIG. 3-VARIATION IN BEND ANGLE AT MAXIMUM LOAD WITH TEMPERATURE OF TEST - E 6010 ELECTRODE. (FLEETWELD 5)-(FOR DETAILS SEE TABLE 3)

DWG. 44E220

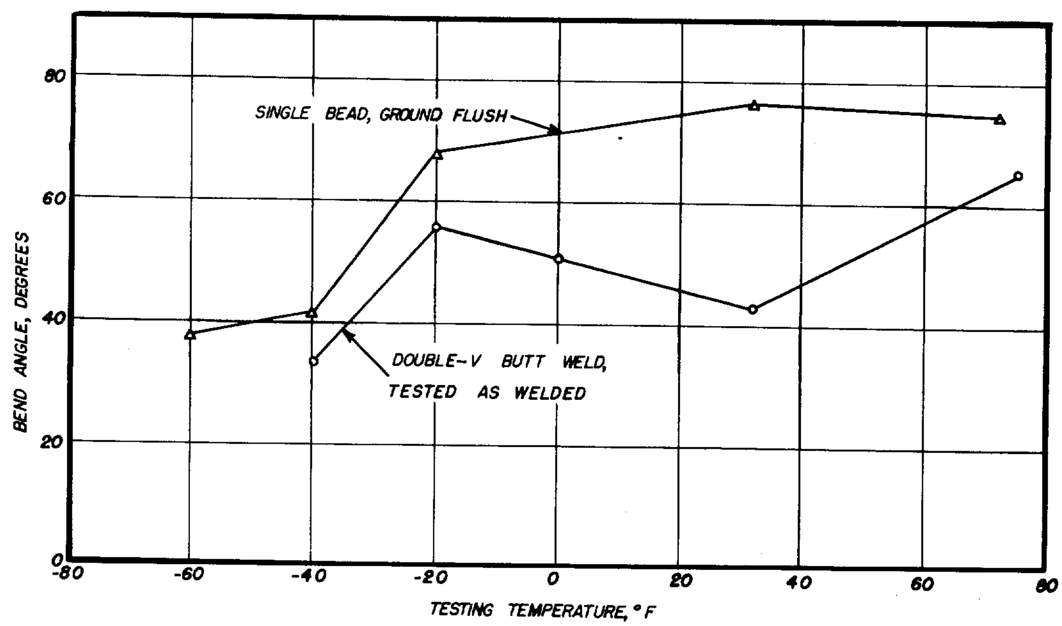


FIG. 4 VARIATION IN BEND ANGLE AT MAXIMUM LOAD WITH TEMPERATURE OF TEST -UNIONMELT BEADS AND WELDS-(FOR DETAILS SEE TABLE 4)

DWG. 44E223

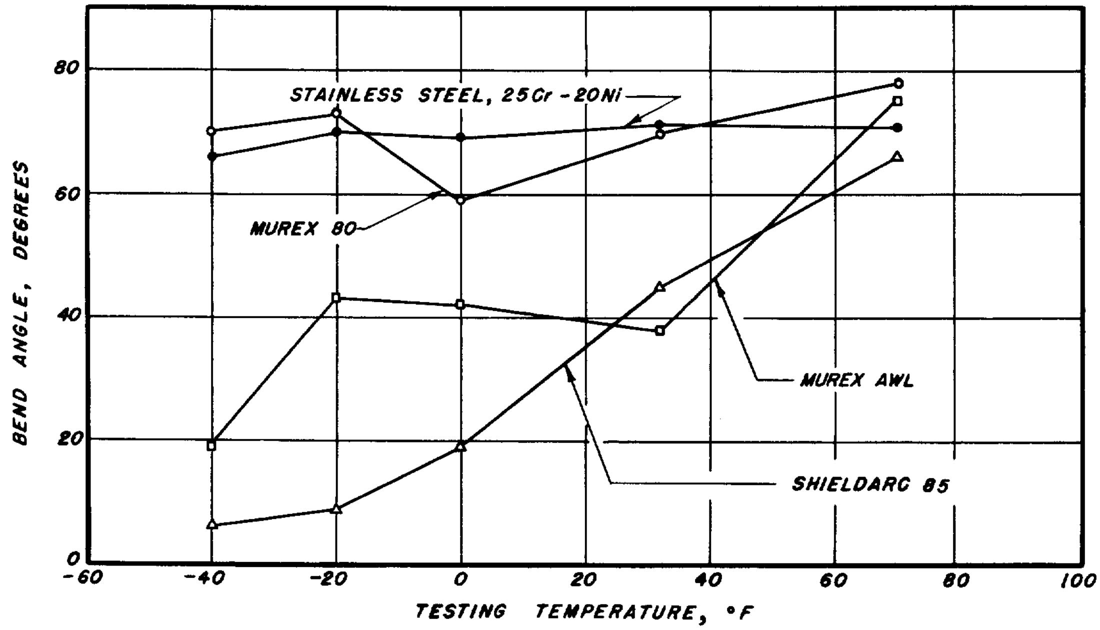


FIG. 5 — VARIATION IN BEND ANGLE AT MAXIMUM LOAD WITH TEMPERATURE OF TEST — ALLOY ELECTRODES. - (FOR DETAILS SEE TABLE 6)

FIG. 5

DWG. 44E224

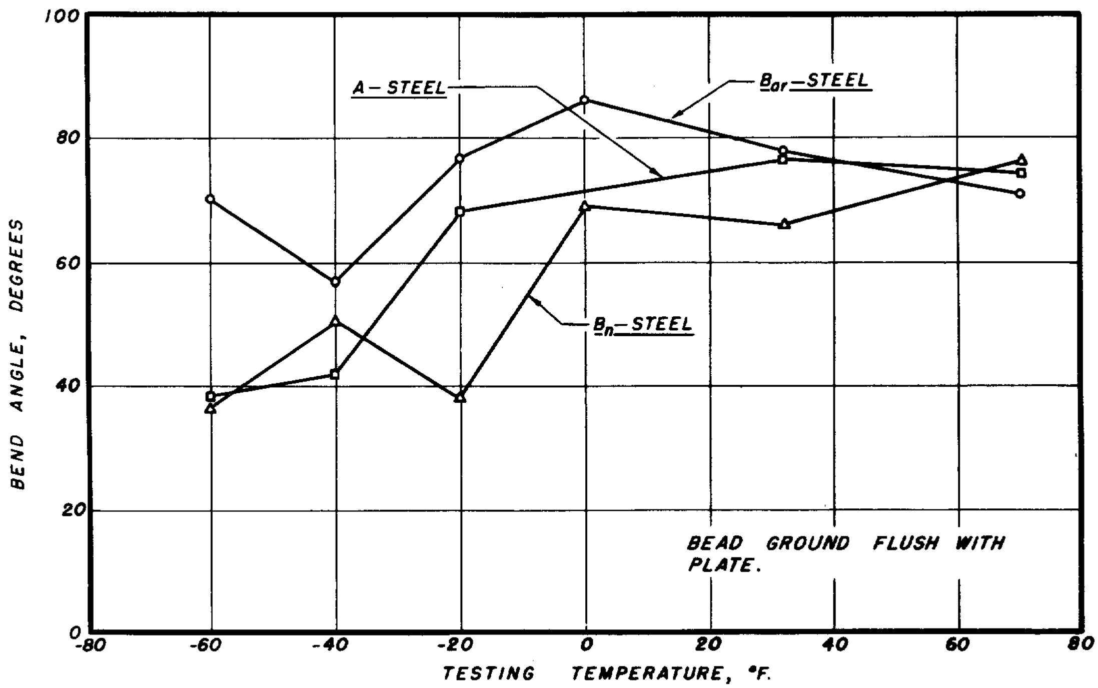
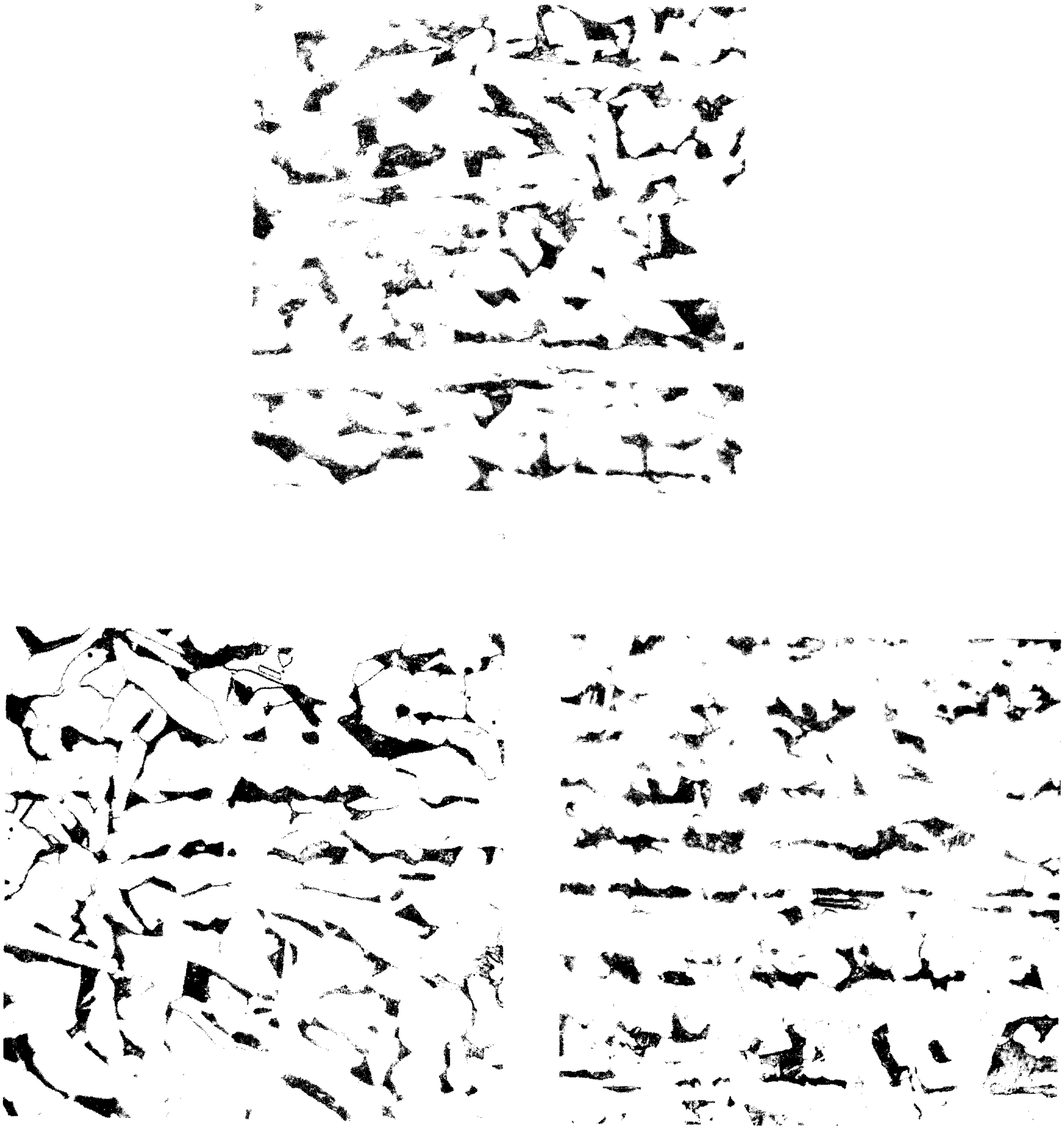


FIG. 6—VARIATION IN BEND ANGLE AT MAXIMUM LOAD WITH TEMPERATURE OF TEST FOR THREE PLATE MATERIALS. (UNIONMELT BEADS)
(FOR DETAILS SEE TABLE 7)

FIG. 6

DWG. 44E222



Bn

FIG. 7 -- Photo[illegible] of Steels A, B as rolled and B normalized ([illegible] X)

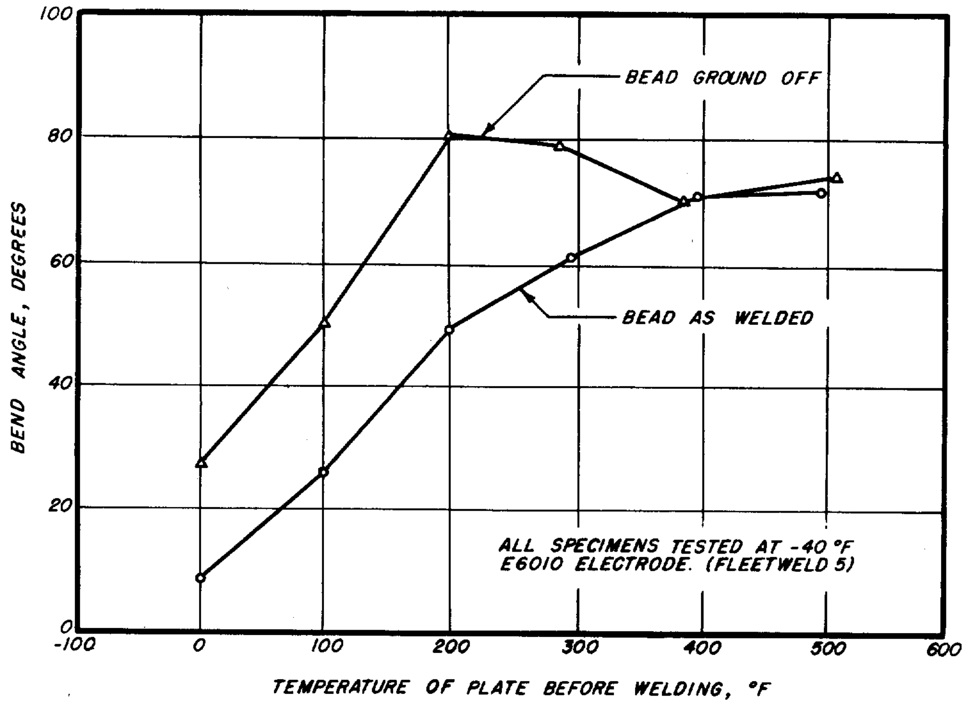


FIG. 8

FIG. 8—VARIATION IN BEND ANGLE AT MAXIMUM LOAD WITH PREHEAT TEMPERATURE—SINGLE WELD BEADS.—(FOR DETAILS SEE TABLE 8)

DWG. 44E225

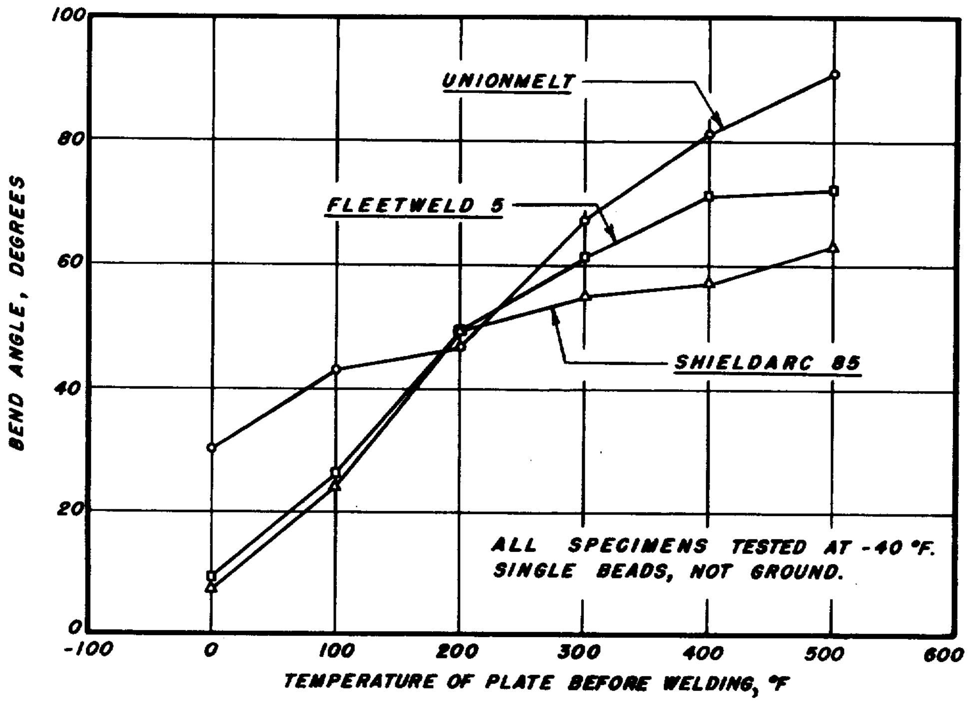


FIG. 9

FIG. 9—VARIATION IN BEND ANGLE AT MAXIMUM LOAD WITH PREHEAT TEMPERATURE—THREE TYPES OF ELECTRODES.
(FOR DETAILS SEE TABLE 8)

DWG. 44E221

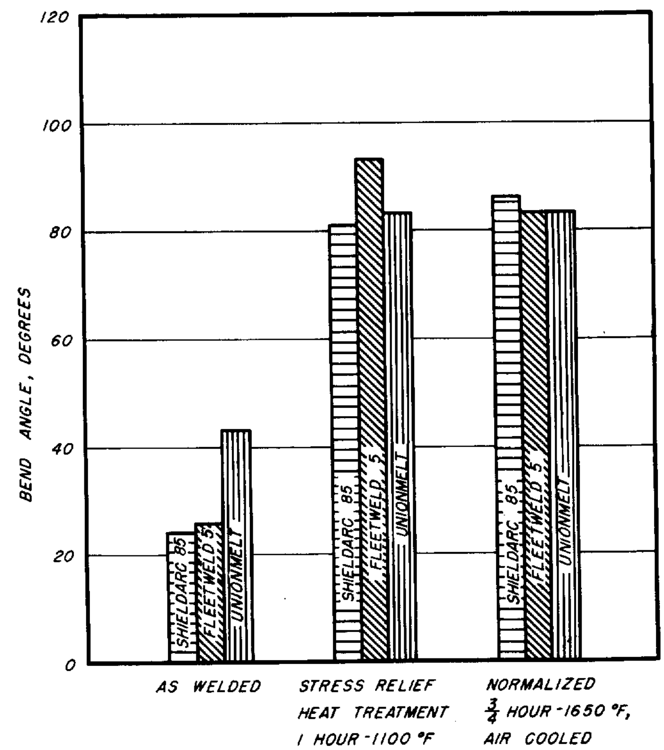


FIG. 10 - EFFECT OF HEAT TREATMENT AFTER WELDING ON DUCTILITY IN THE BEND TEST.
(FOR DETAILS SEE TABLE 8)

DWG. 44E226 FIG. 10

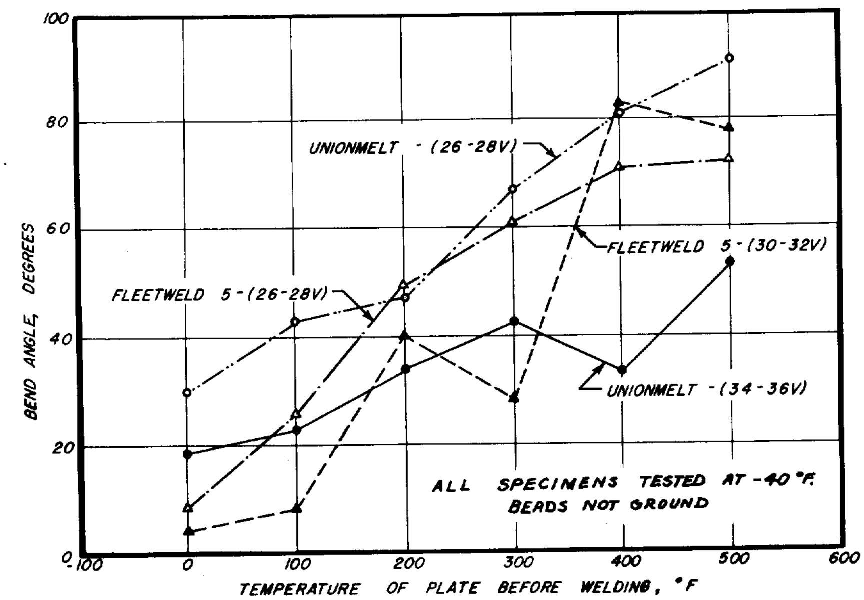


FIG. 11 - VARIATION IN BEND ANGLE AT MAXIMUM LOAD WITH PRE-HEAT TEMPERATURE FOR DIFFERENT ARC VOLTAGES AND TWO TYPES OF WELD. - (FOR DETAILS SEE TABLE 9)

FIG. 11

DWG. 44E227

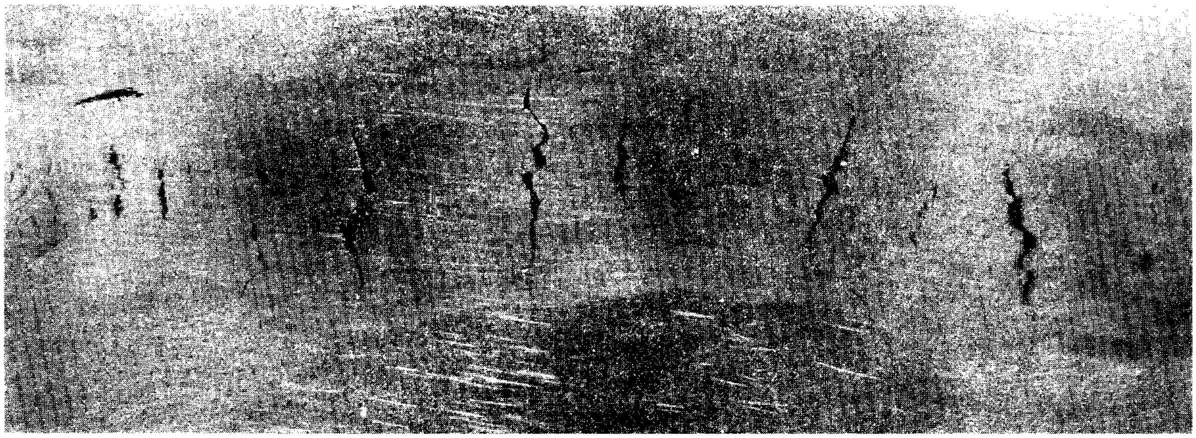


FIG. 12 -- Typical Cracks Formed in Weld Metal During Bend Test

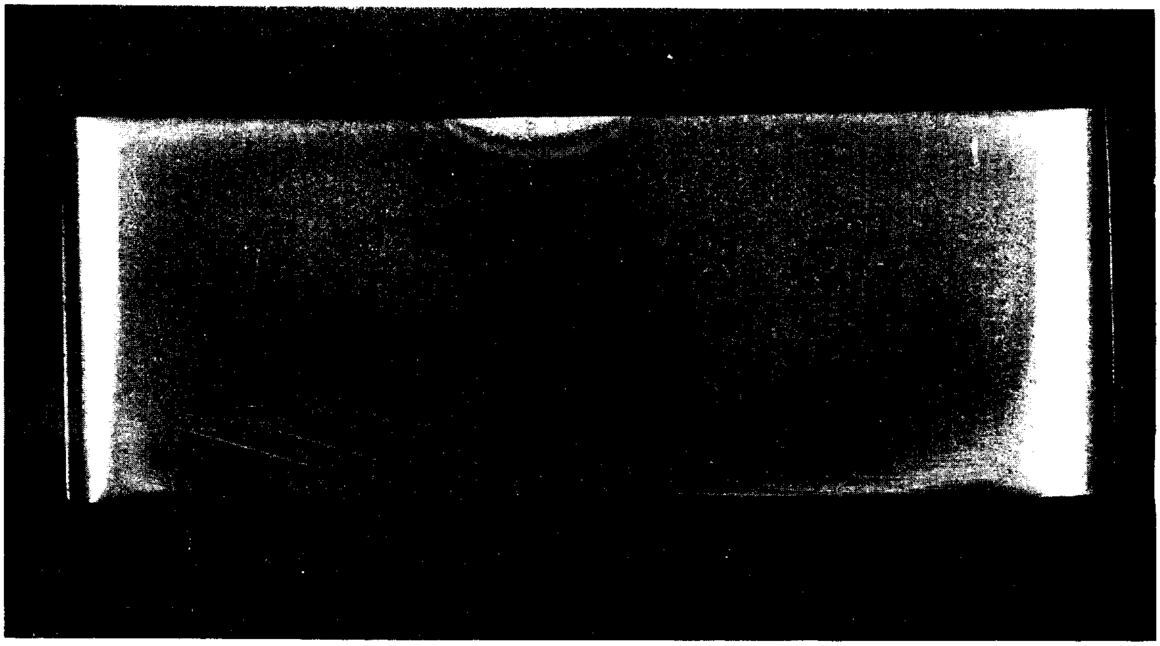


FIG. 13 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 2 ($\frac{3}{4}$-INCH PLATE)

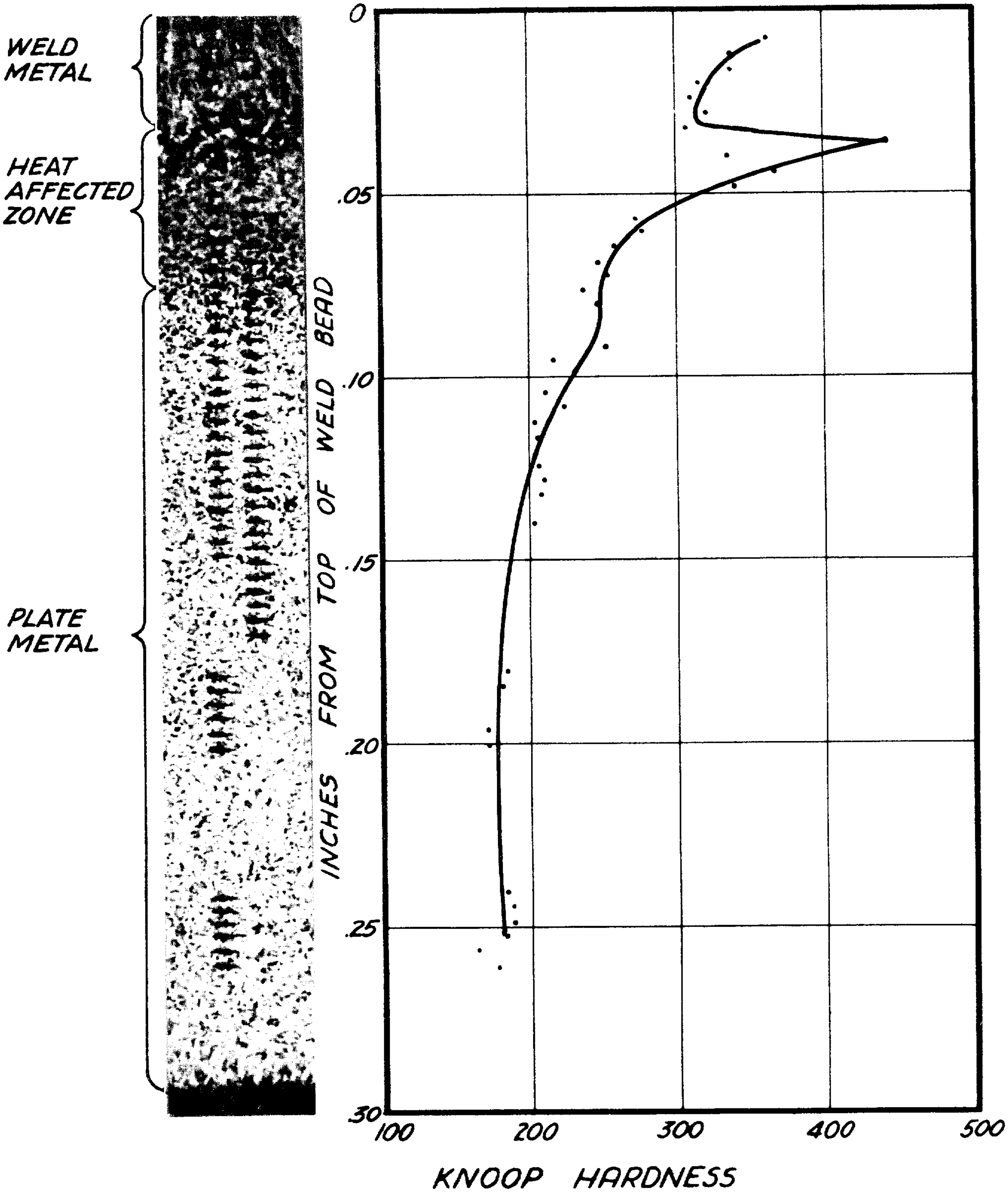


FIG. 14 - SPECIMEN 2; FLEETWELD 5 ELECTRODE
(SEE TABLE-3)

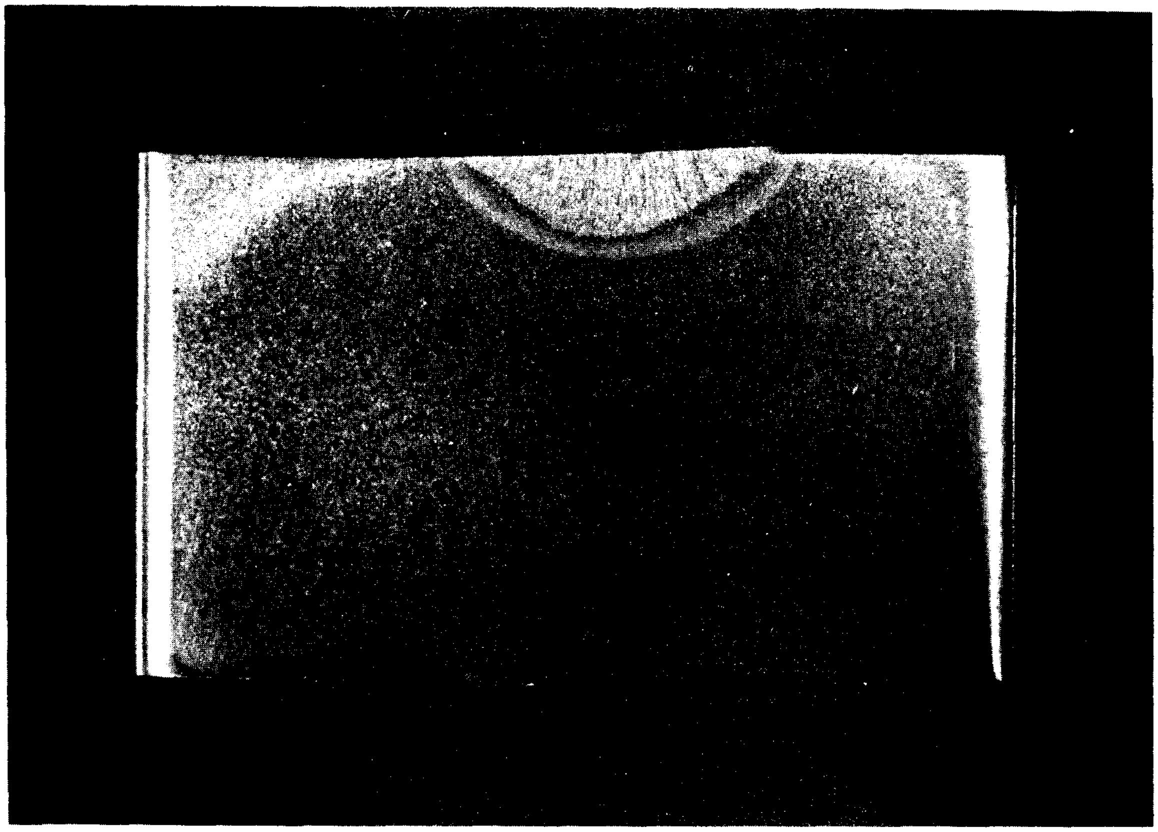


FIG. 15 - CROSS-SECTION OF WELD BEAD, SPECIMEN 25 ($\frac{3}{4}$-INCH PLATE)

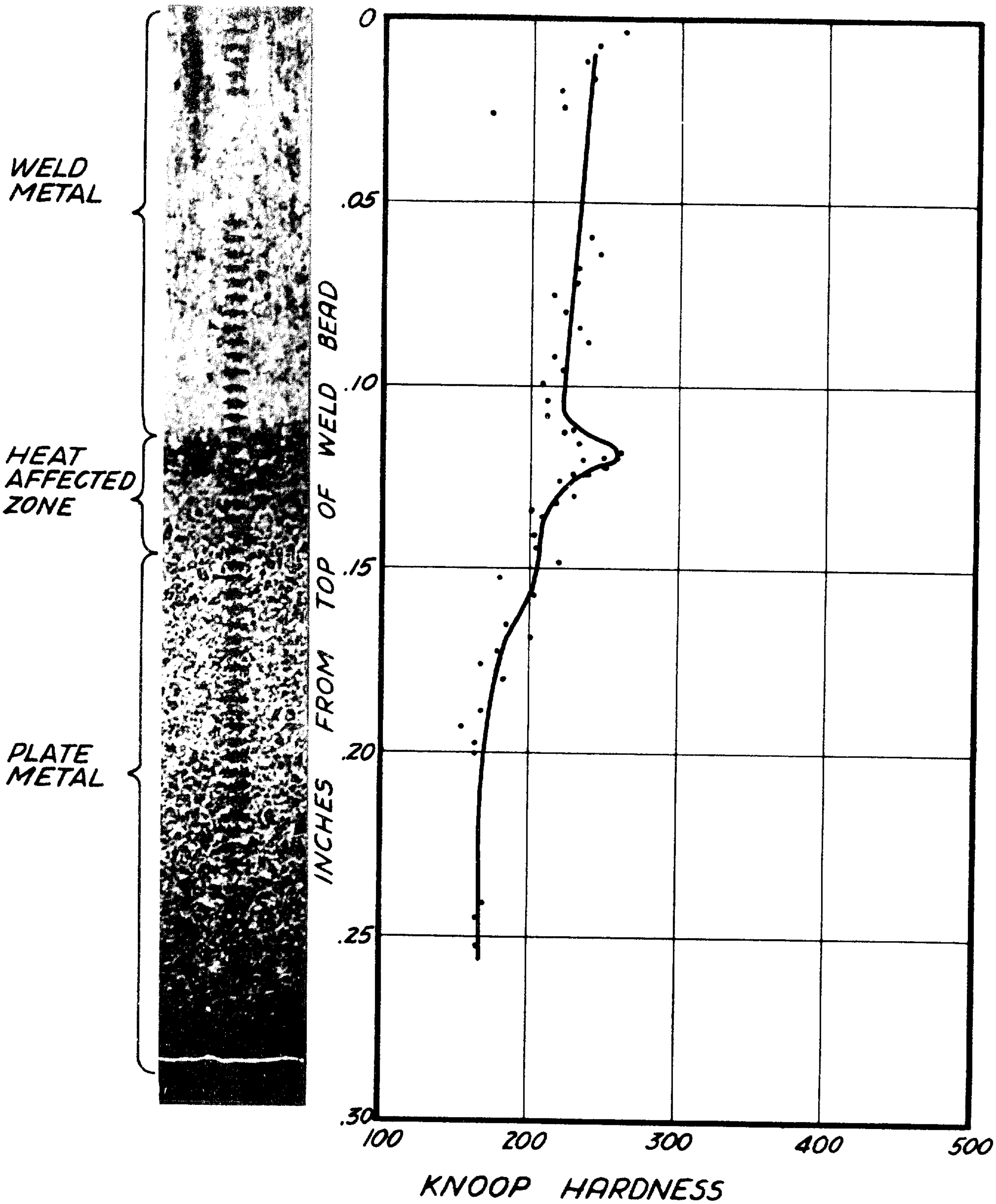


FIG. 16 - SPECIMEN 25; UNIONMELT ELECTRODE.
(SEE TABLE 4)

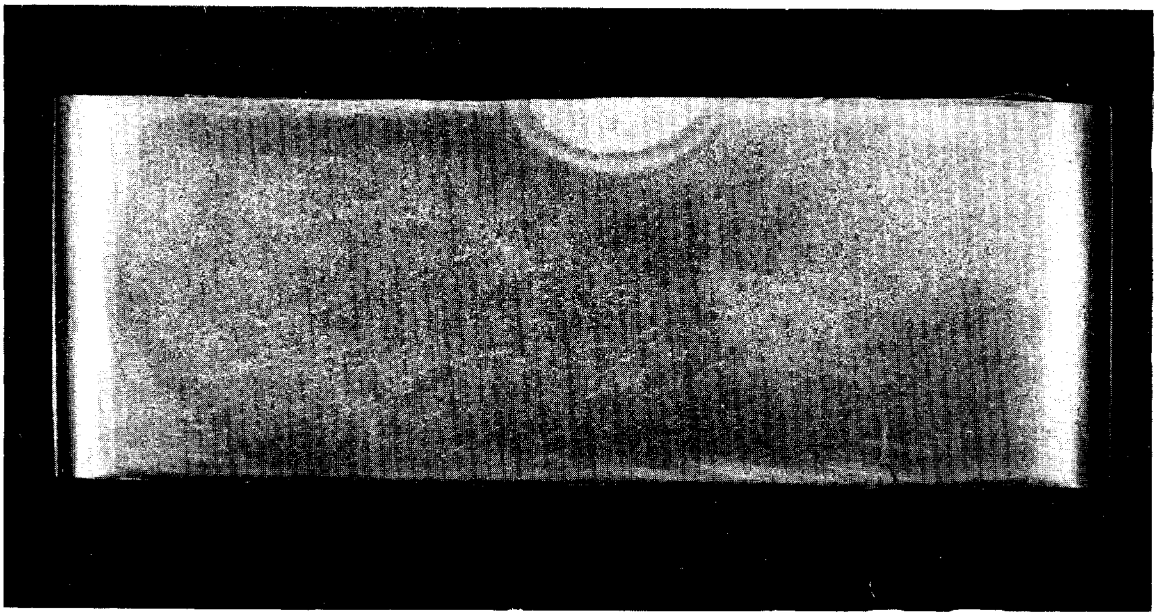


FIG. 17 - CROSS-SECTION OF WELD BEAD, SPECIMEN 32 ($\frac{3}{4}$-INCH PLATE)

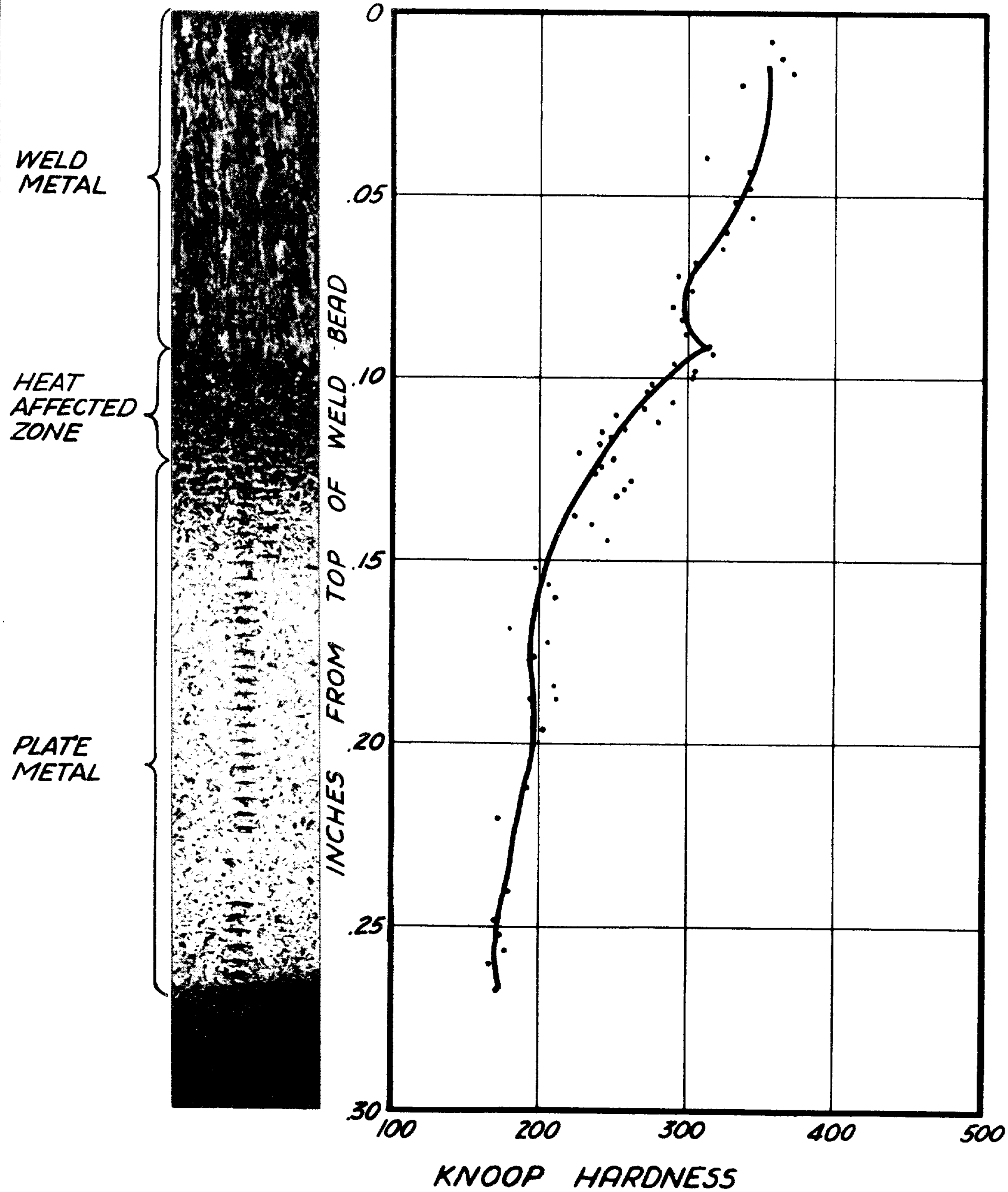


FIG. 18 -SPECIMEN 32; SHIELDARC 85 ELECTRODE; (SEE TABLE 6)

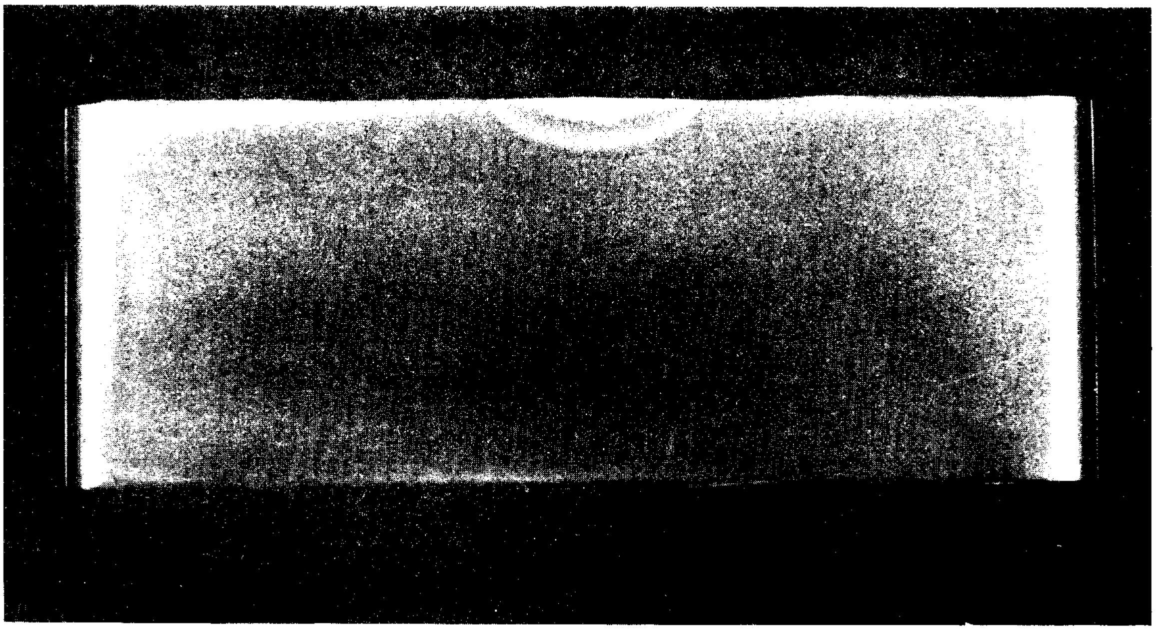


FIG. 19 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 37 ($\frac{3}{4}$-INCH PLATE)

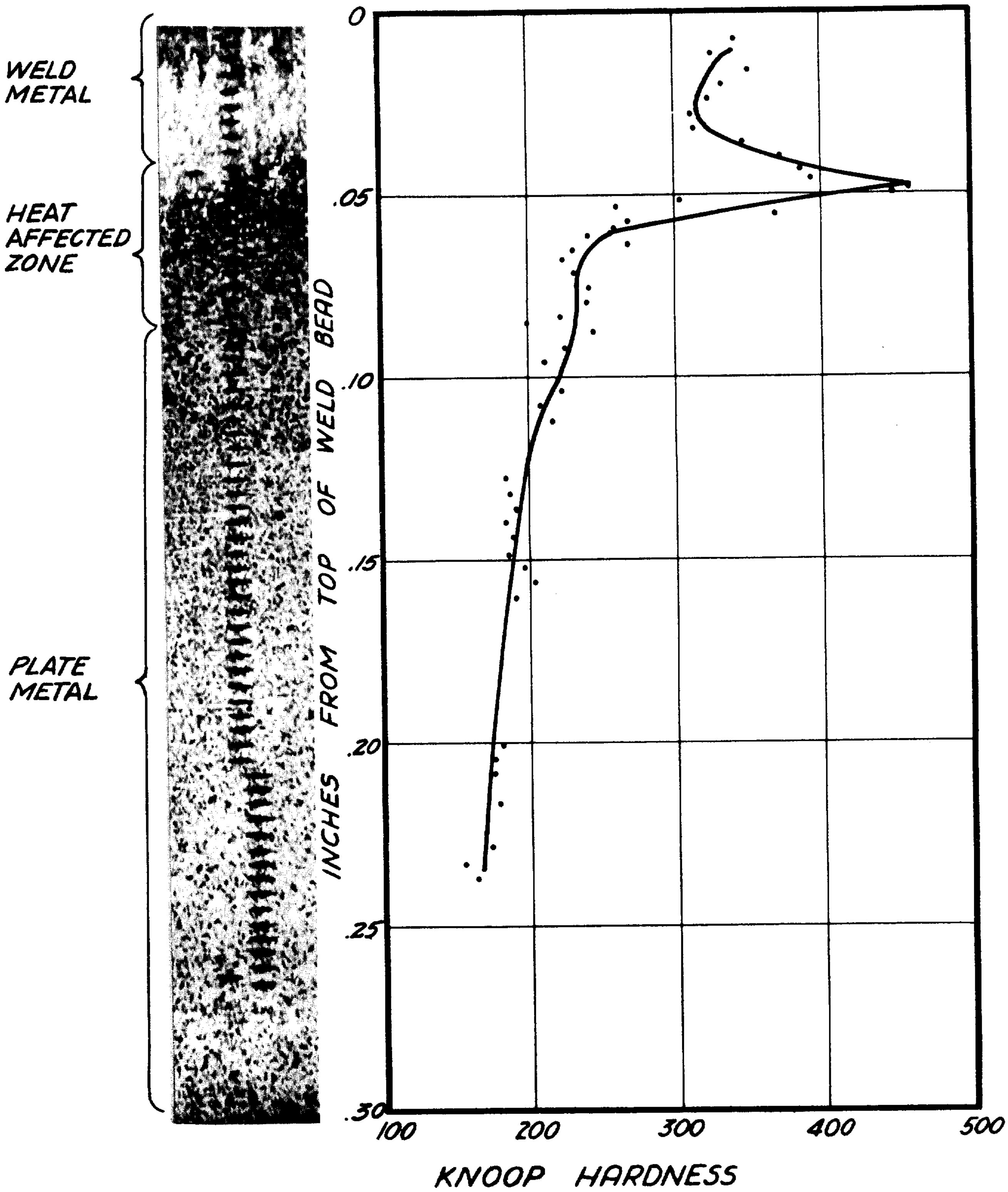


FIG. 20 - SPECIMEN 37; MUREX 80 ELECTRODE;
(SEE TABLE 6)

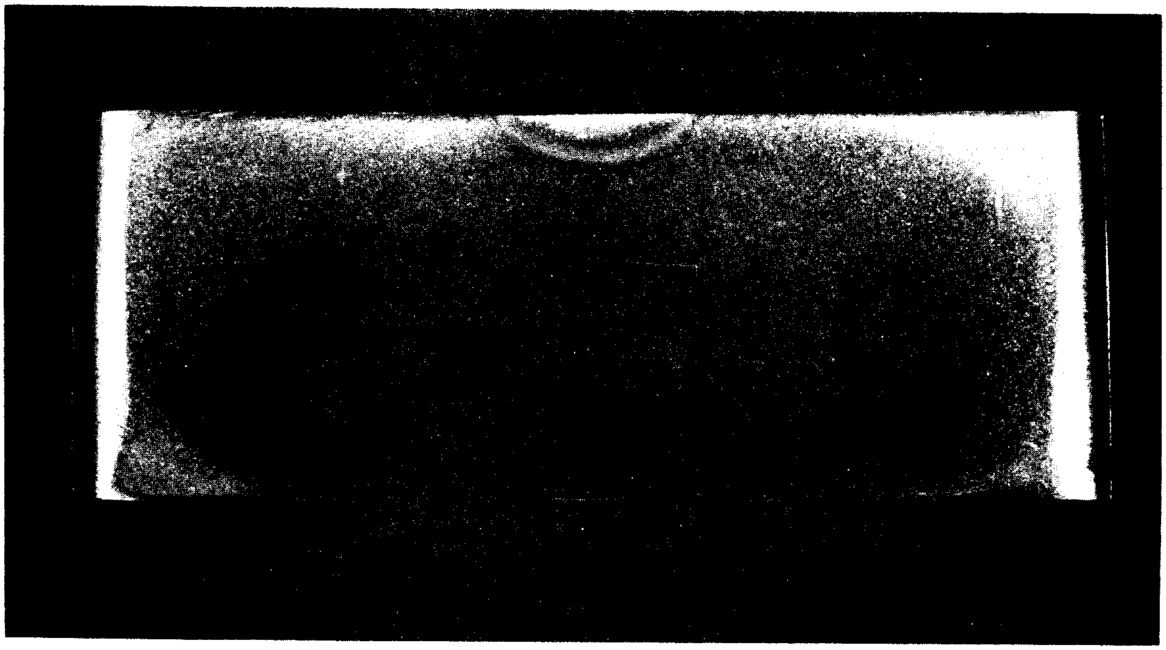


FIG. 21 - CROSS-SECTION OF WELD BEAD, SPECIMEN 42 ($\frac{3}{4}$-INCH PLATE)

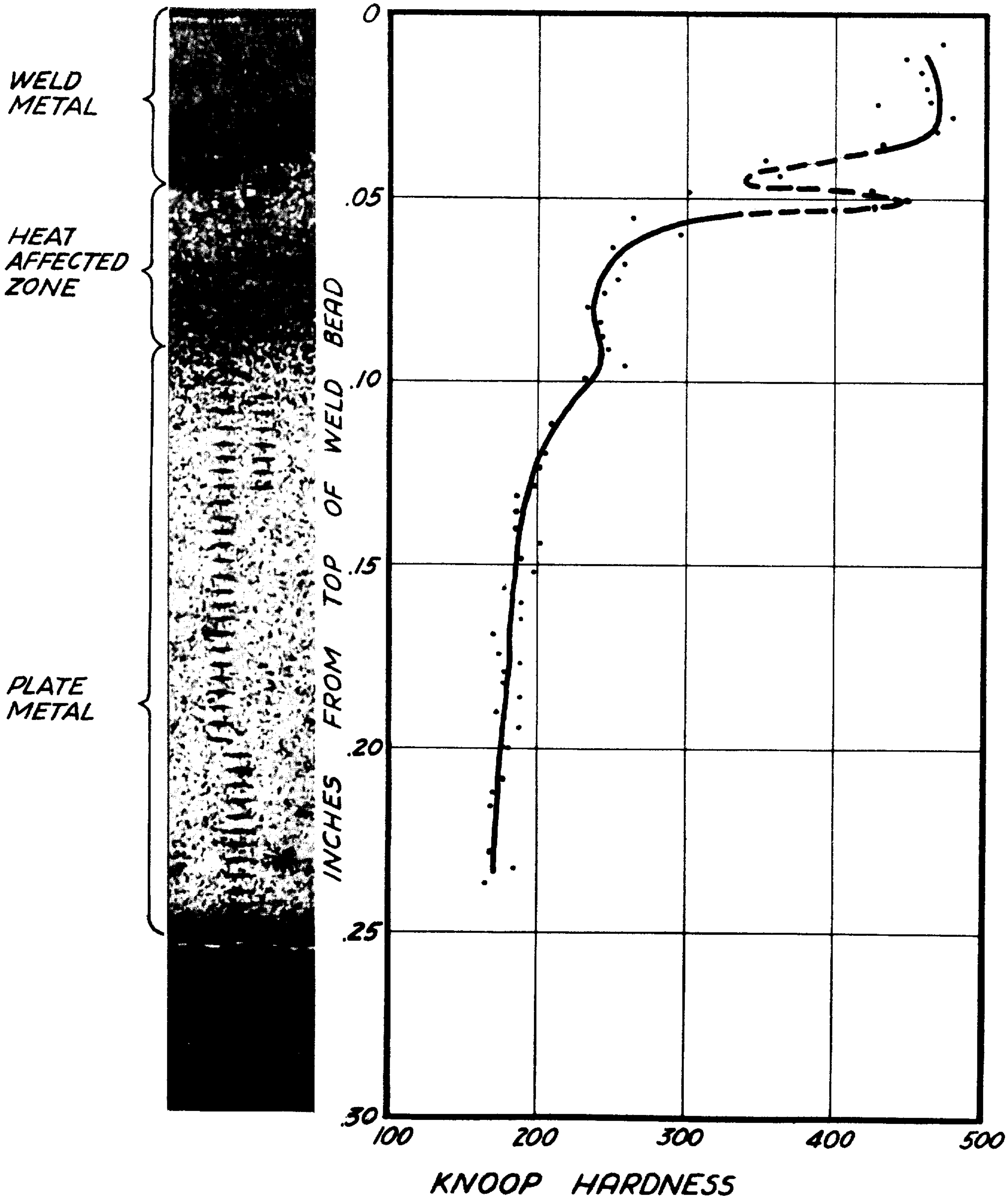


FIG. 22-SPECIMEN 42; MUREX AWL ELECTRODE,
(SEE TABLE 6)

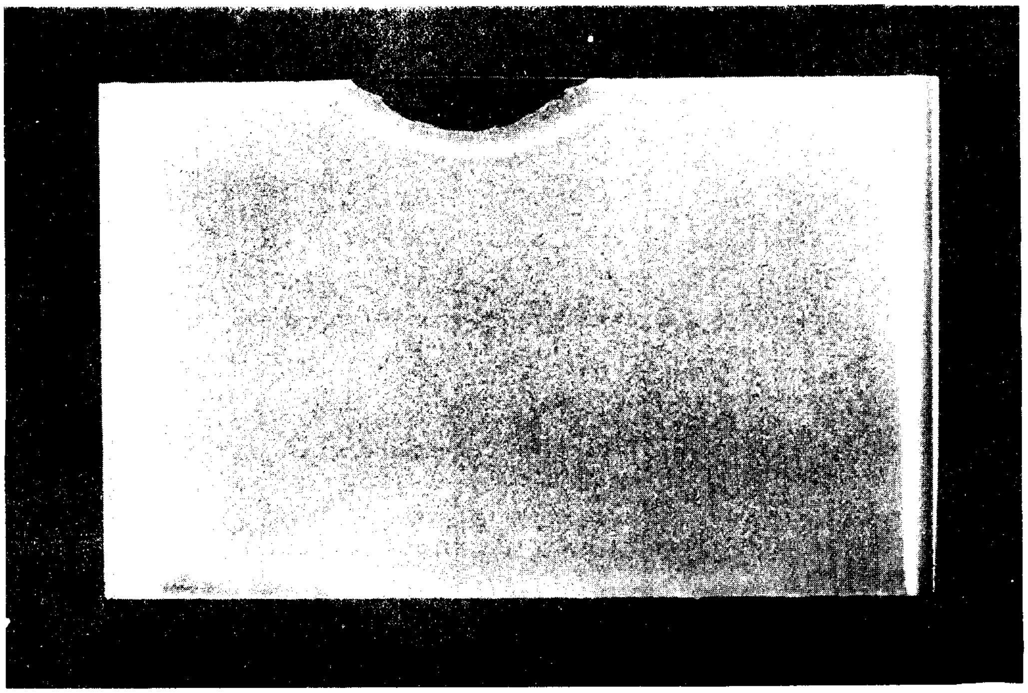


FIG. 23 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 51 ($\frac{3}{4}$-INCH PLATE)

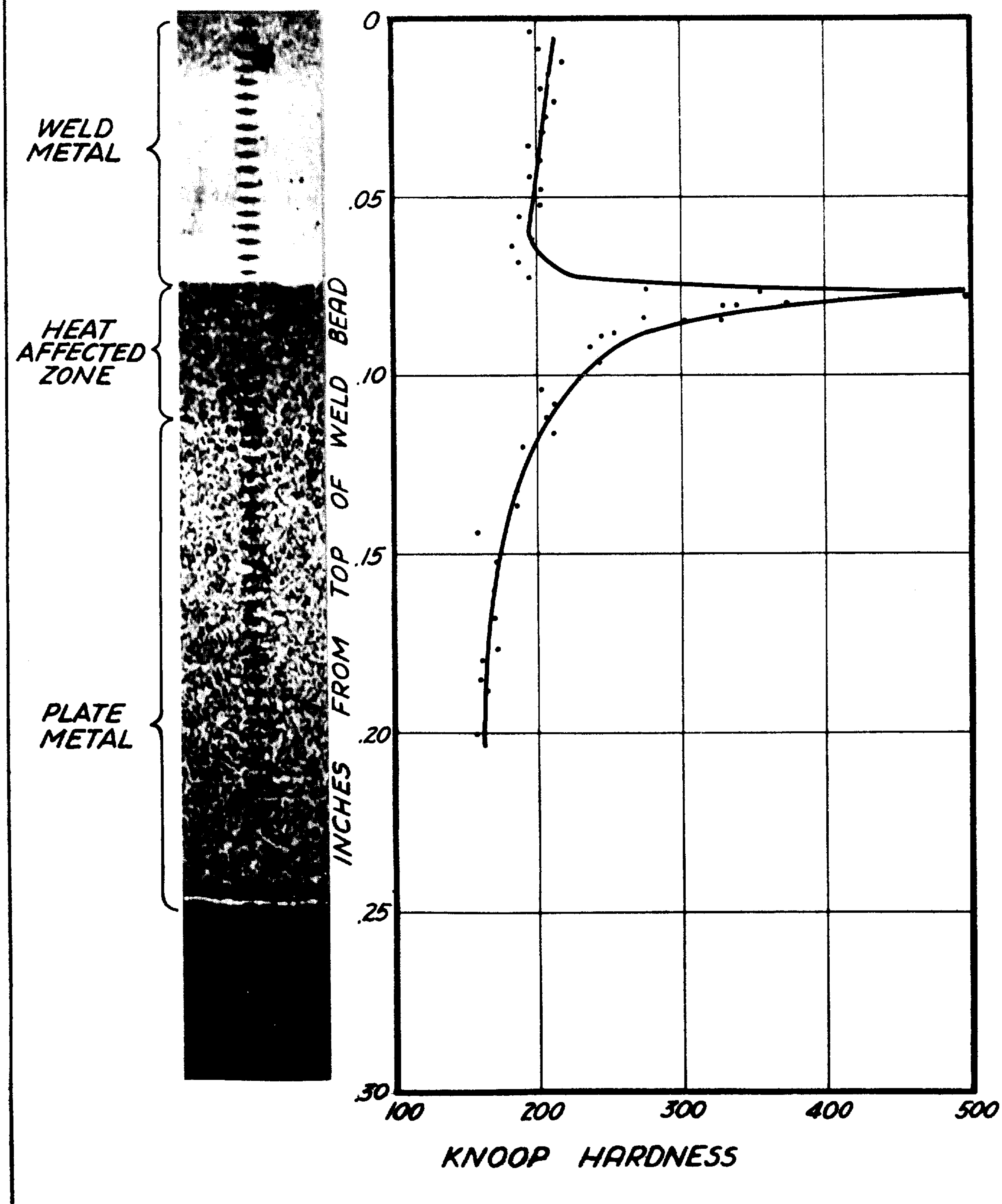


FIG. 24-SPECIMEN 51; 25 Cr. – 20 Ni. ELECTRODE;
(SEE TABLE 6)

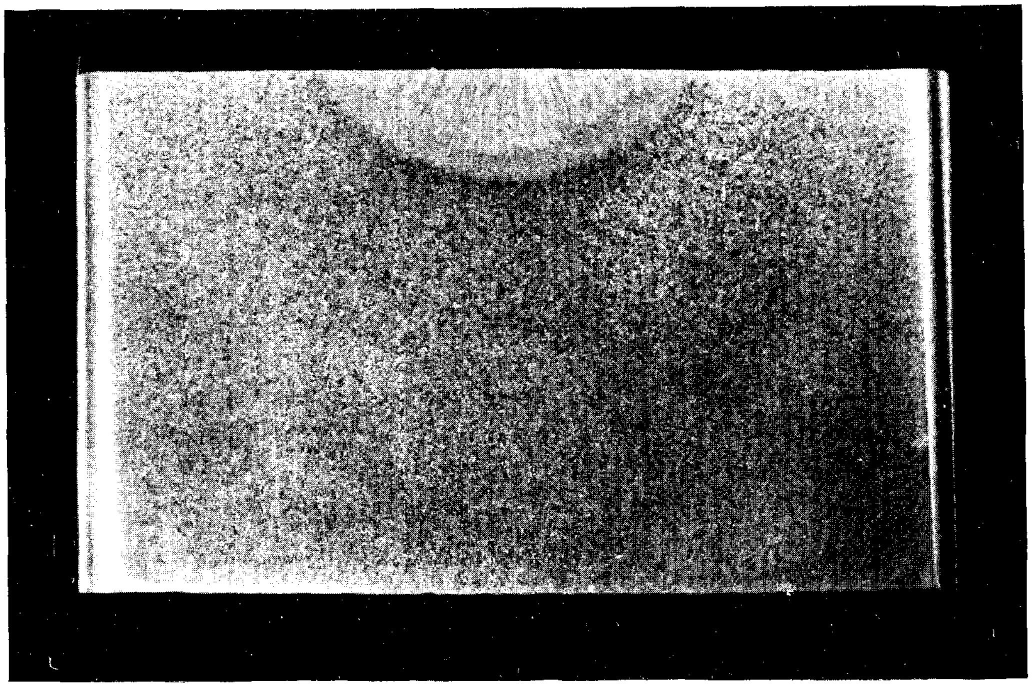


FIG. 25 - CROSS-SECTION OF WELD BEAD, SPECIMEN 52 ($\frac{3}{4}$-INCH PLATE)

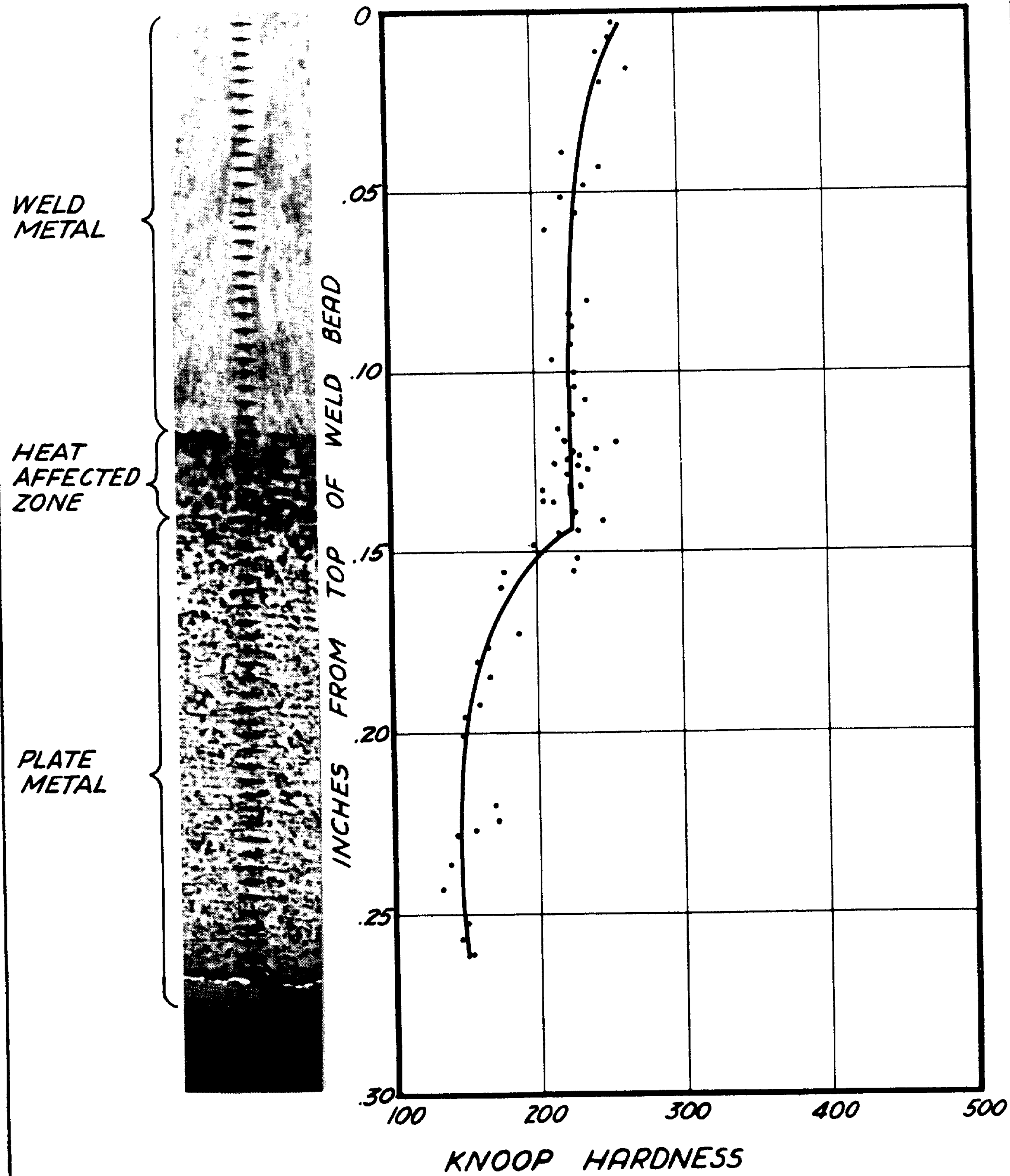


FIG. 26 - SPECIMEN 52; UNIONMELT ELECTRODE.
(SEE TABLE 7)

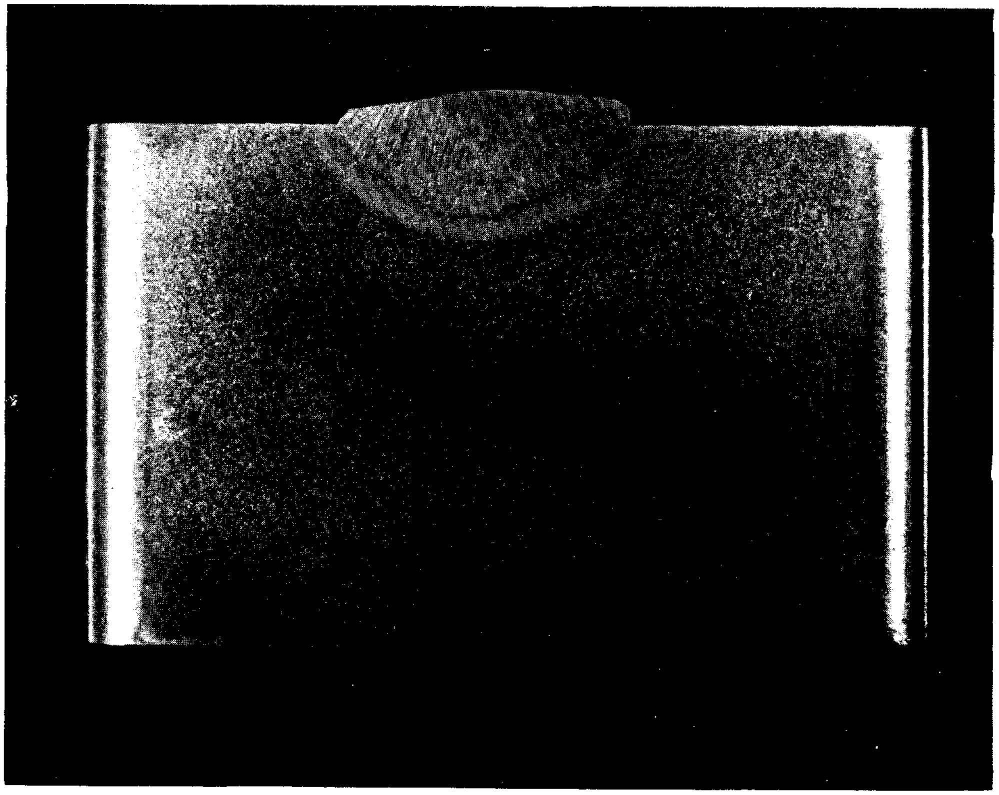


FIG. 27-CROSS-SECTION OF WELD BEAD,
SPECIMEN 58 ($\frac{3}{4}$-INCH PLATE)

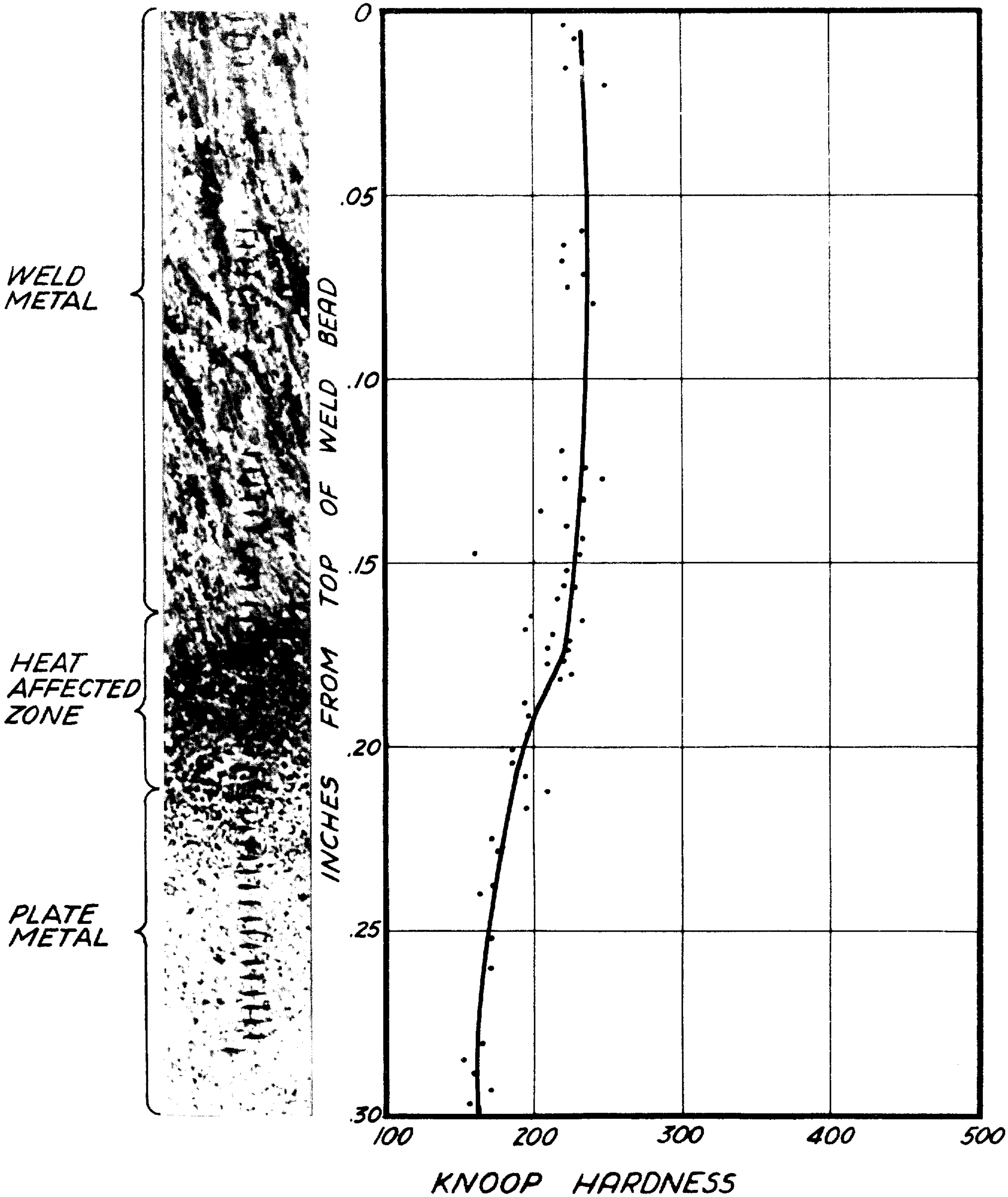


FIG 28- SPECIMEN 58; UNIONMELT ELECTRODE.
(SEE TABLE 7)

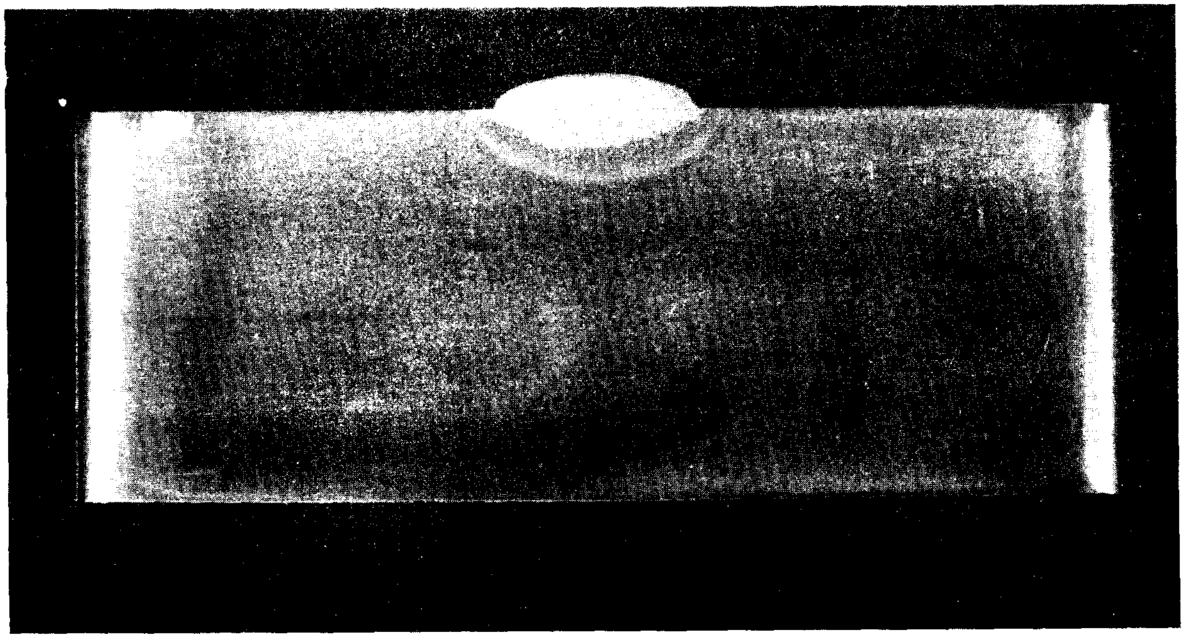


FIG. 29 - CROSS-SECTION OF WELD BEAD, SPECIMEN 70 ($\frac{3}{4}$-INCH PLATE)

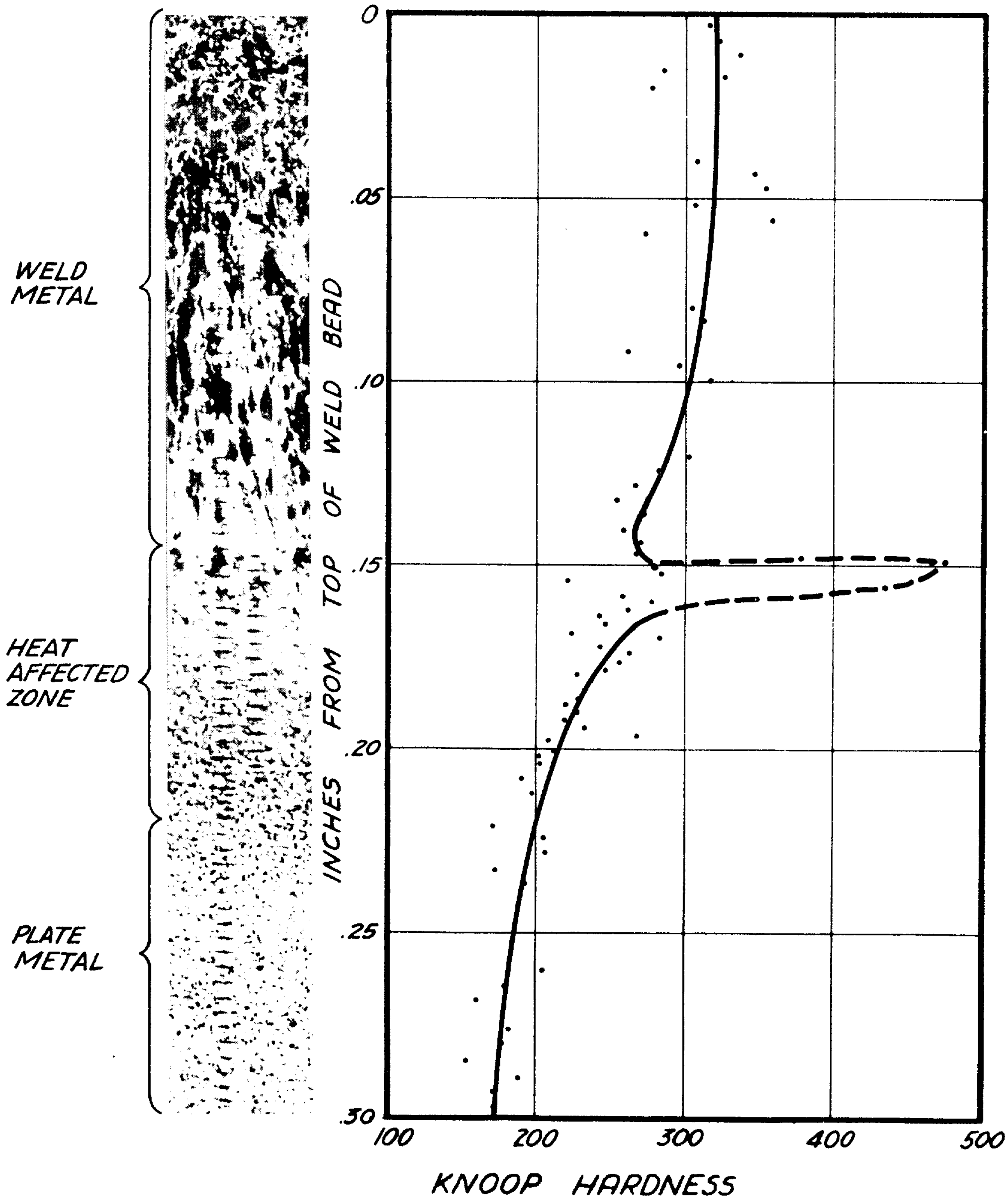


FIG. 30 - SPECIMEN 70; FLEETWELD 5 ELECTRODE; 0°F PREHEAT. (SEE TABLE 8)

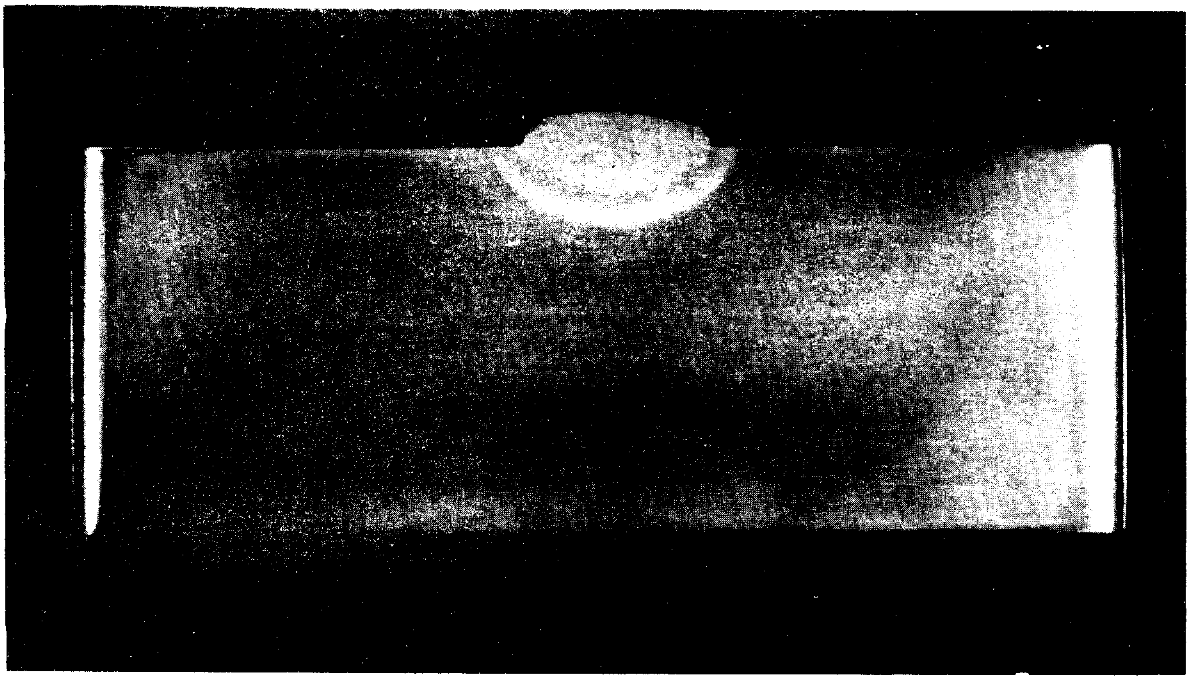


FIG. 31 - CROSS-SECTION OF WELD BEAD, SPECIMEN 71 ($\frac{3}{4}$-INCH PLATE)

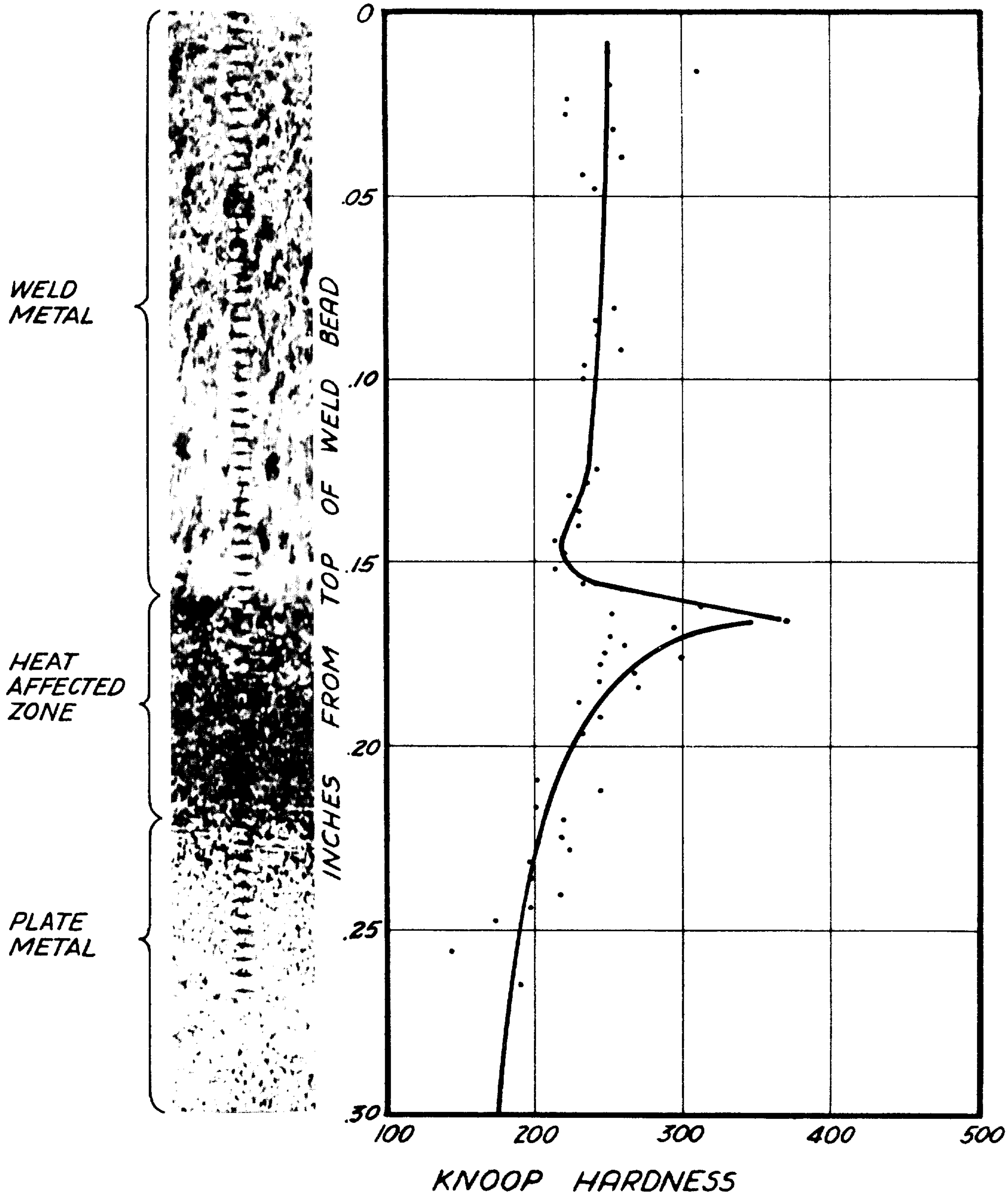


FIG. 32 - SPECIMEN 71; FLEETWELD 5 ELECTRODE; 100 °F PREHEAT. (SEE TABLE 8)

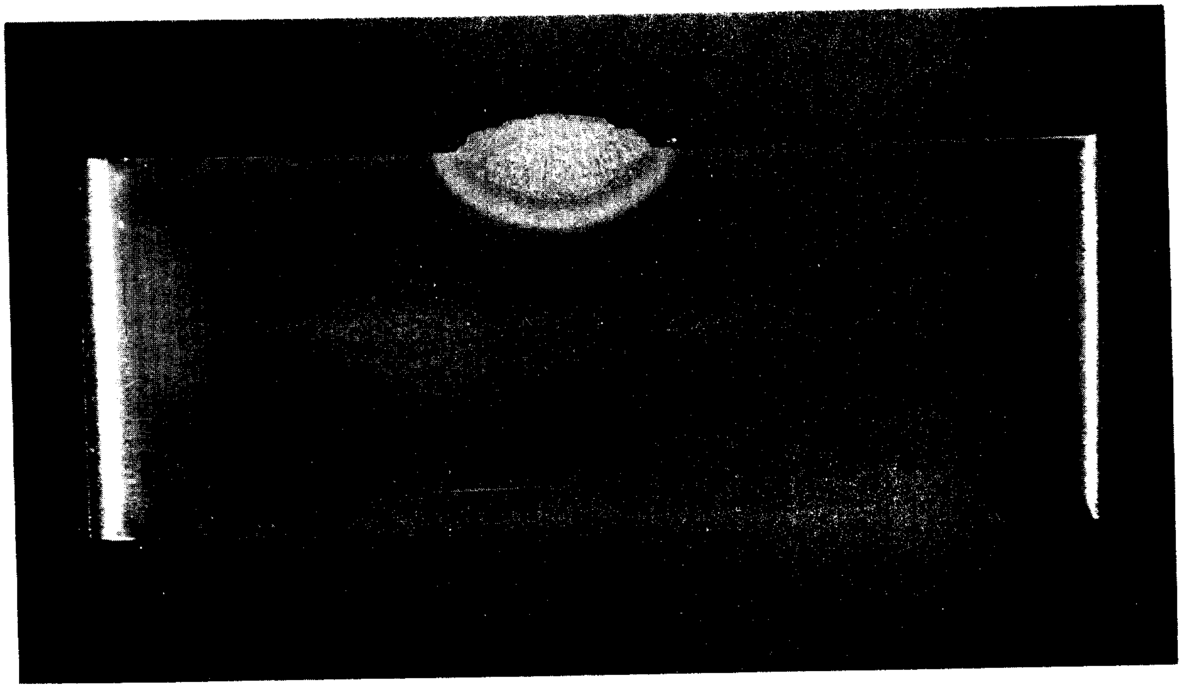


FIG. 33 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 72 ($\frac{3}{4}$-INCH PLATE)

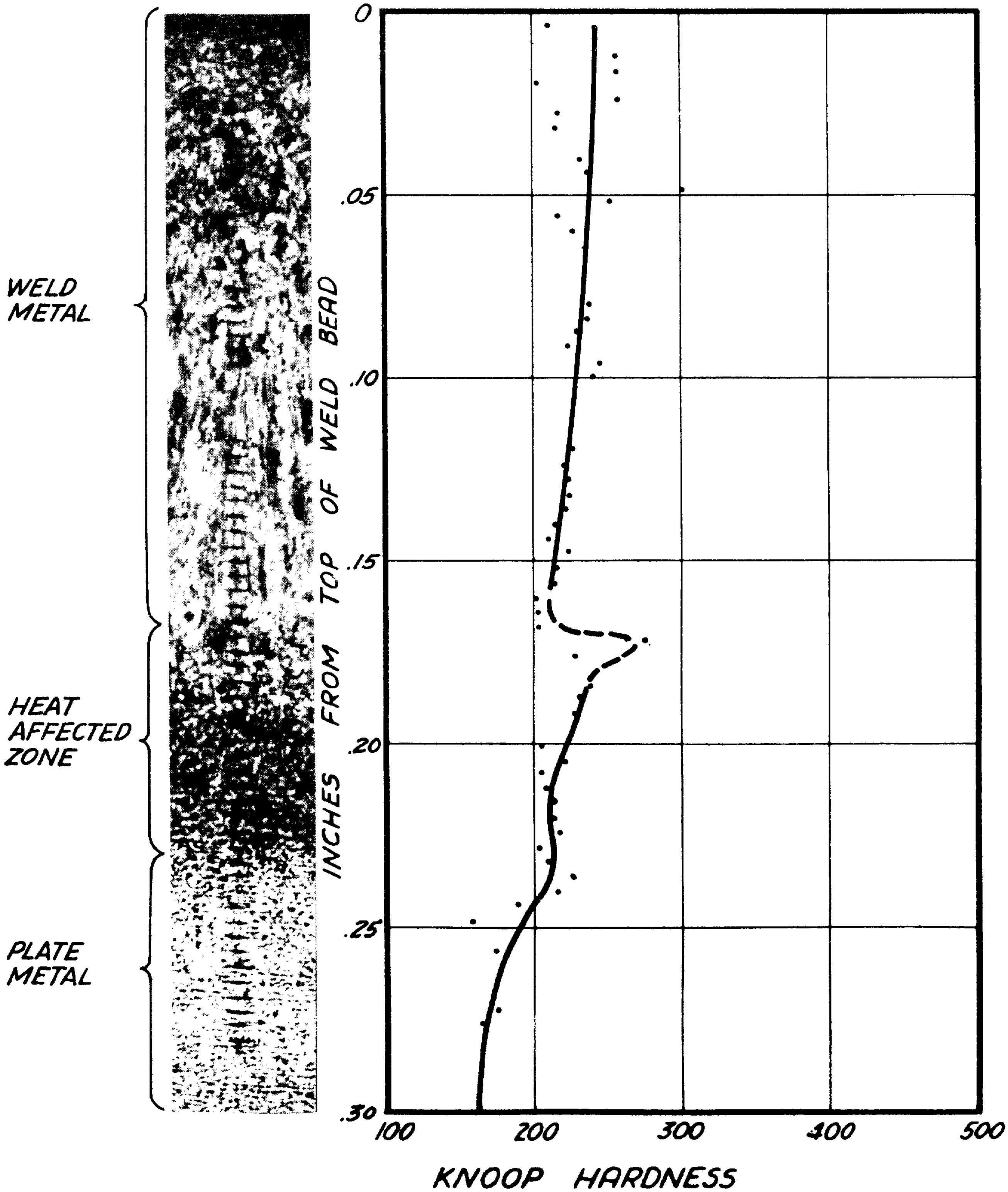


FIG. 34 - SPECIMEN 72; FLEETWELD 5 ELECTRODE; 200 °F PREHEAT. (SEE TABLE 8)

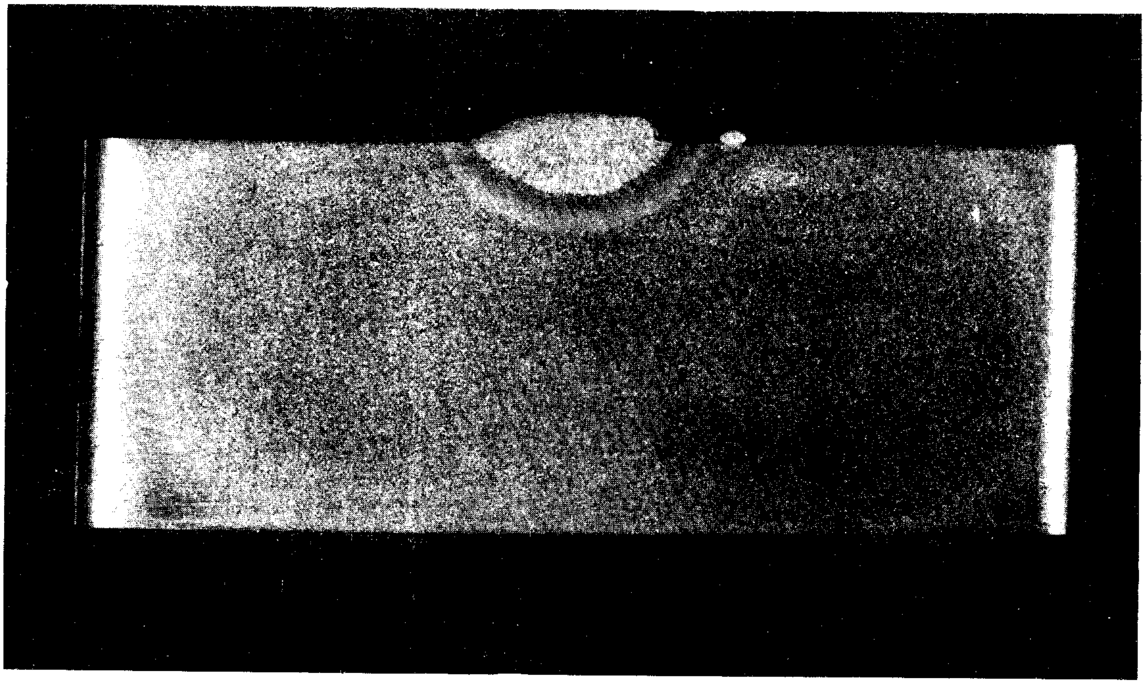


FIG. 35 - CROSS-SECTION OF WELD BEAD, SPECIMEN 73 ($\frac{3}{4}$-INCH PLATE)

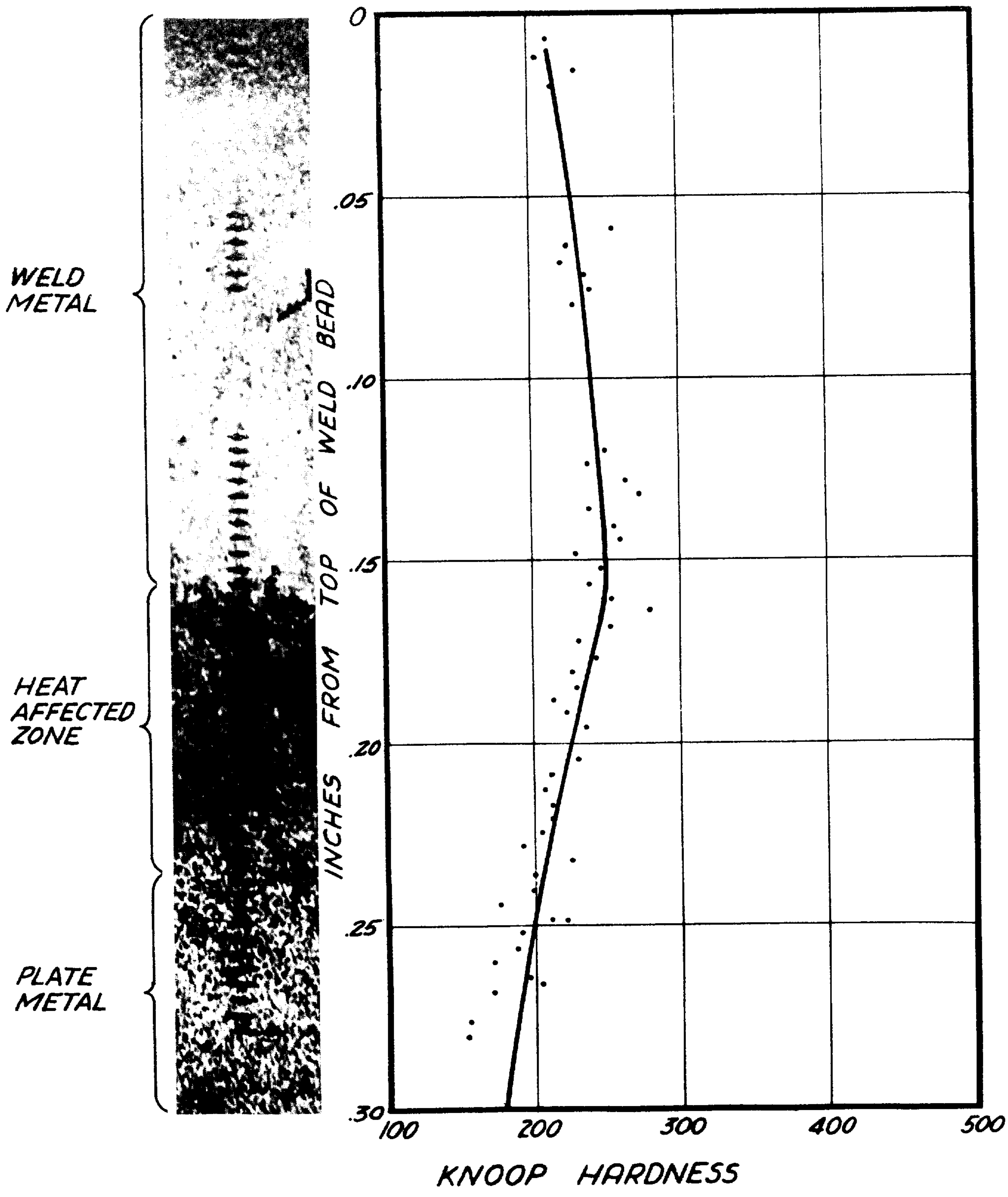


FIG. 36-SPECIMEN 73; FLEETWELD 5 ELECTRODE; 300 °F PREHEAT (SEE TABLE 8)

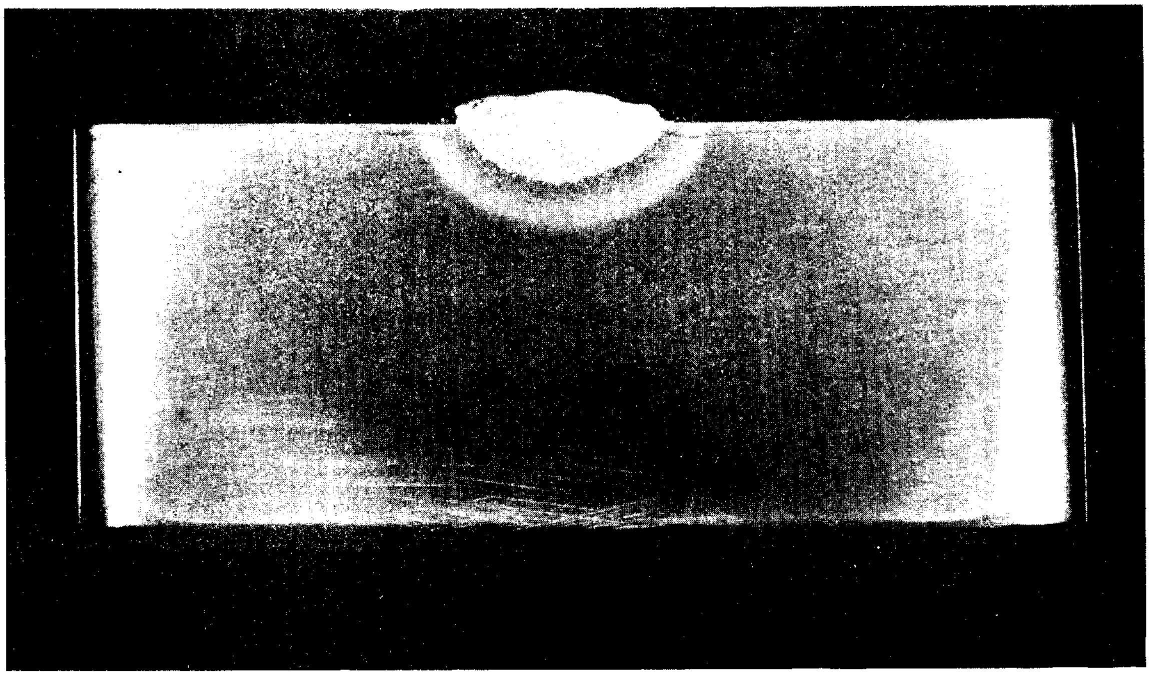


FIG. 37-CROSS-SECTION OF WELD BEAD,
SPECIMEN 74 ($\frac{3}{4}$-INCH PLATE)

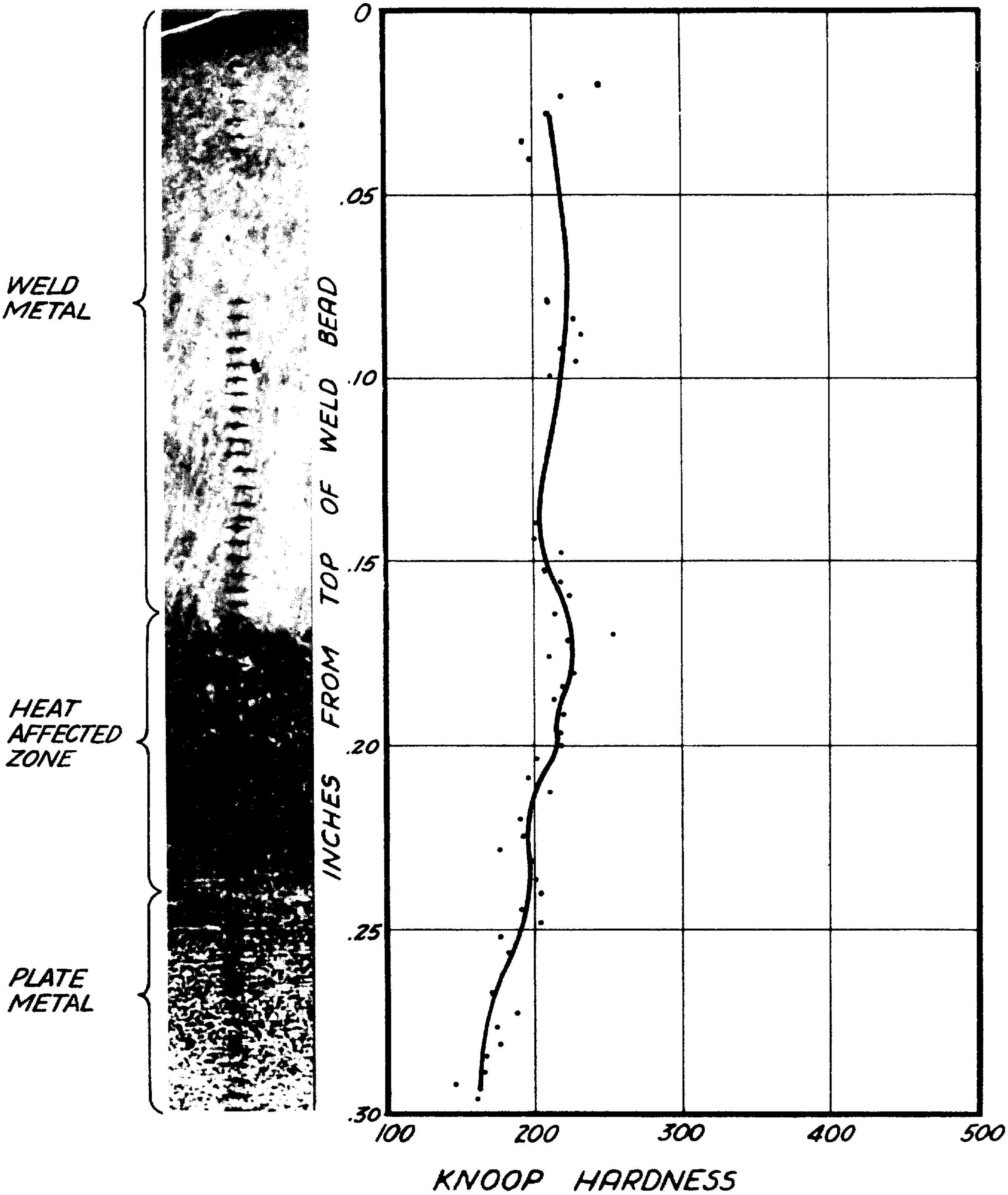


FIG. 38 - SPECIMEN 74; FLEETWELD 5 ELECTRODE; 400 °F PREHEAT. (SEE TABLE 8)

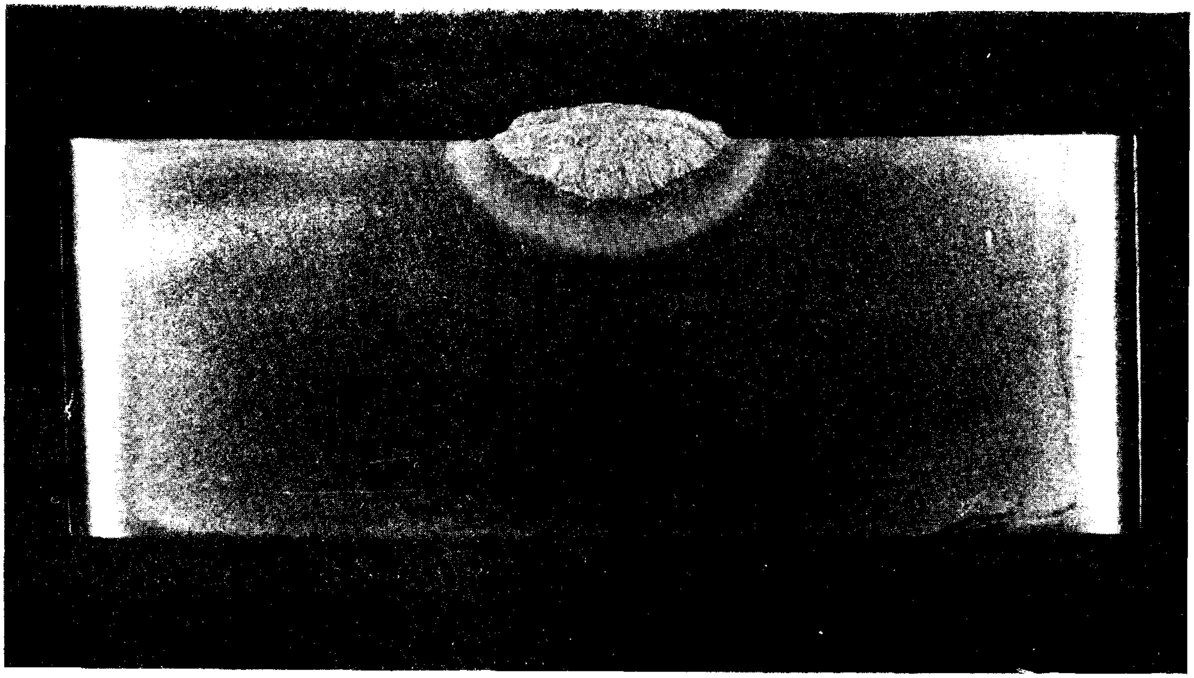


FIG. 39 CROSS SECTION OF WELD BEAD,
SPECIMEN 75 ($\frac{3}{4}$-INCH PLATE)

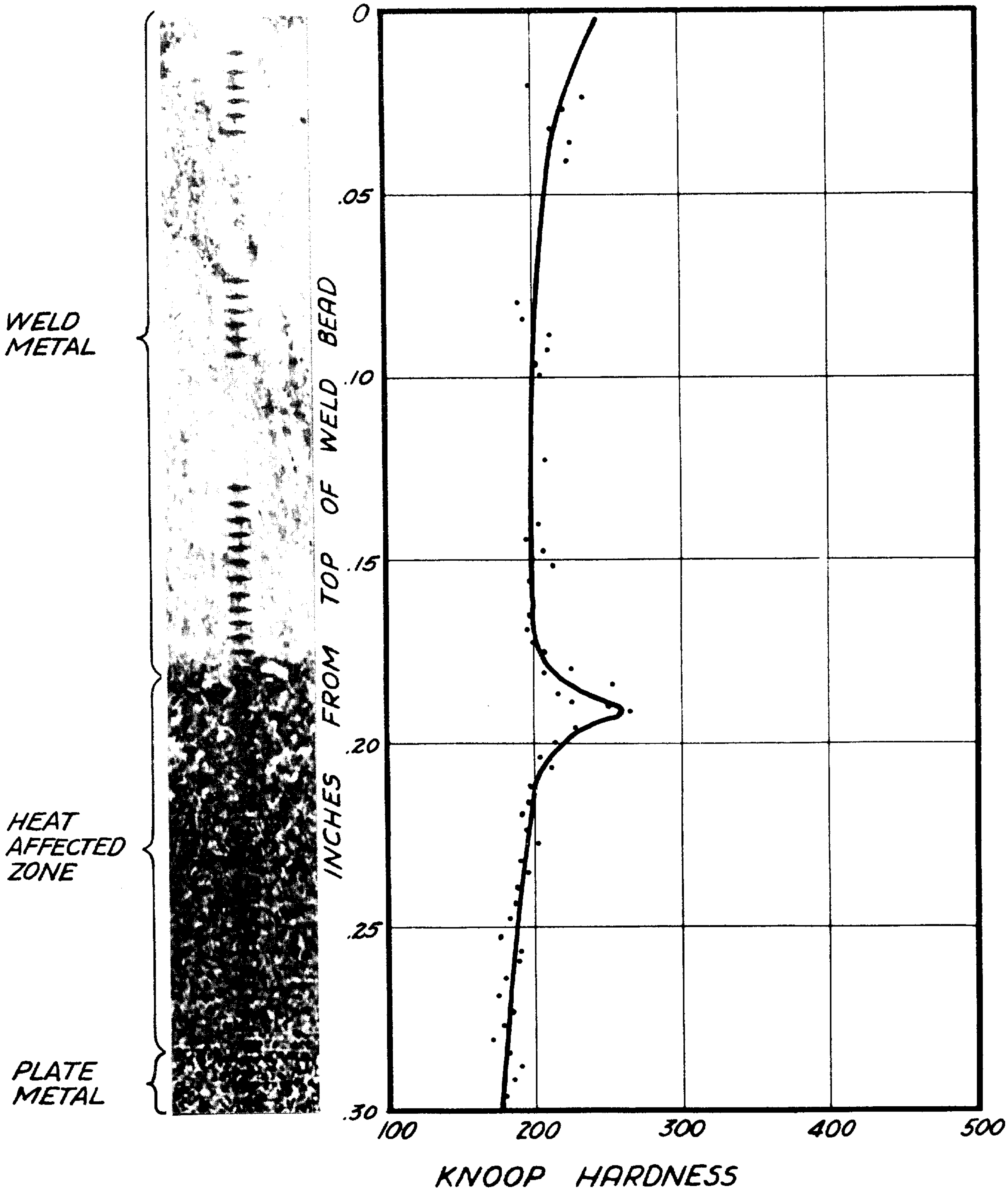


FIG. 40 - SPECIMEN 75; FLEETWELD 5 ELECTRODE; 500 °F PREHEAT. (SEE TABLE 8)

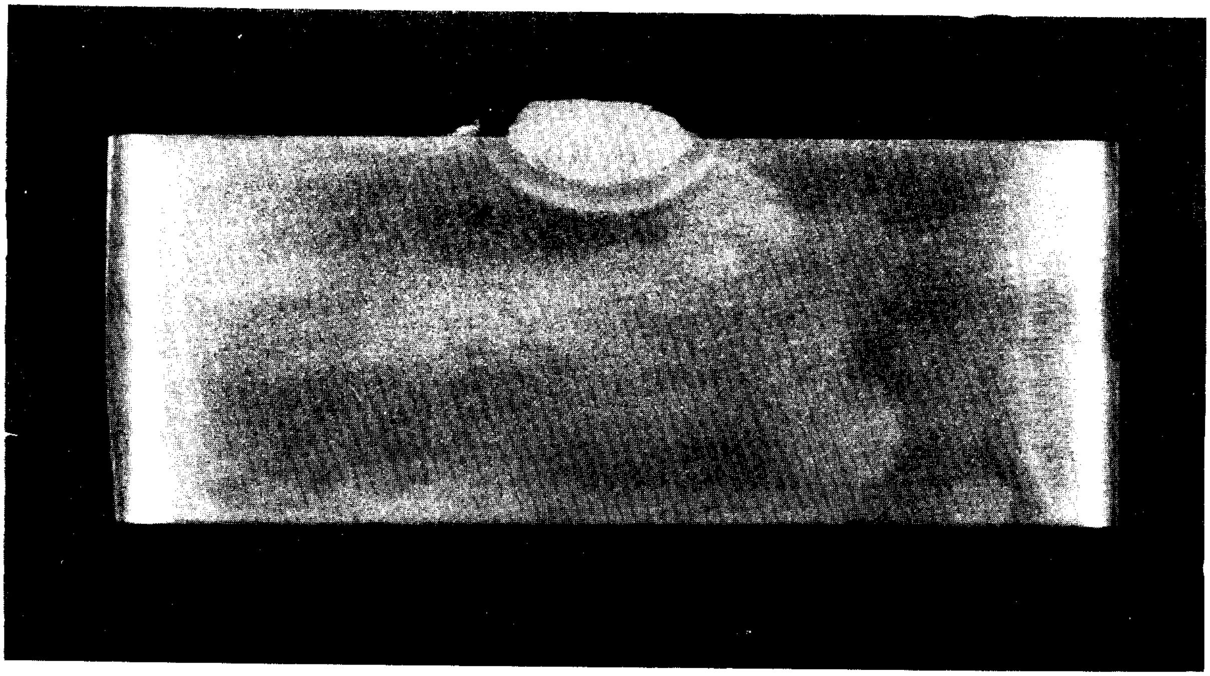


FIG. 41 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 76 ($\frac{3}{4}$-INCH PLATE)

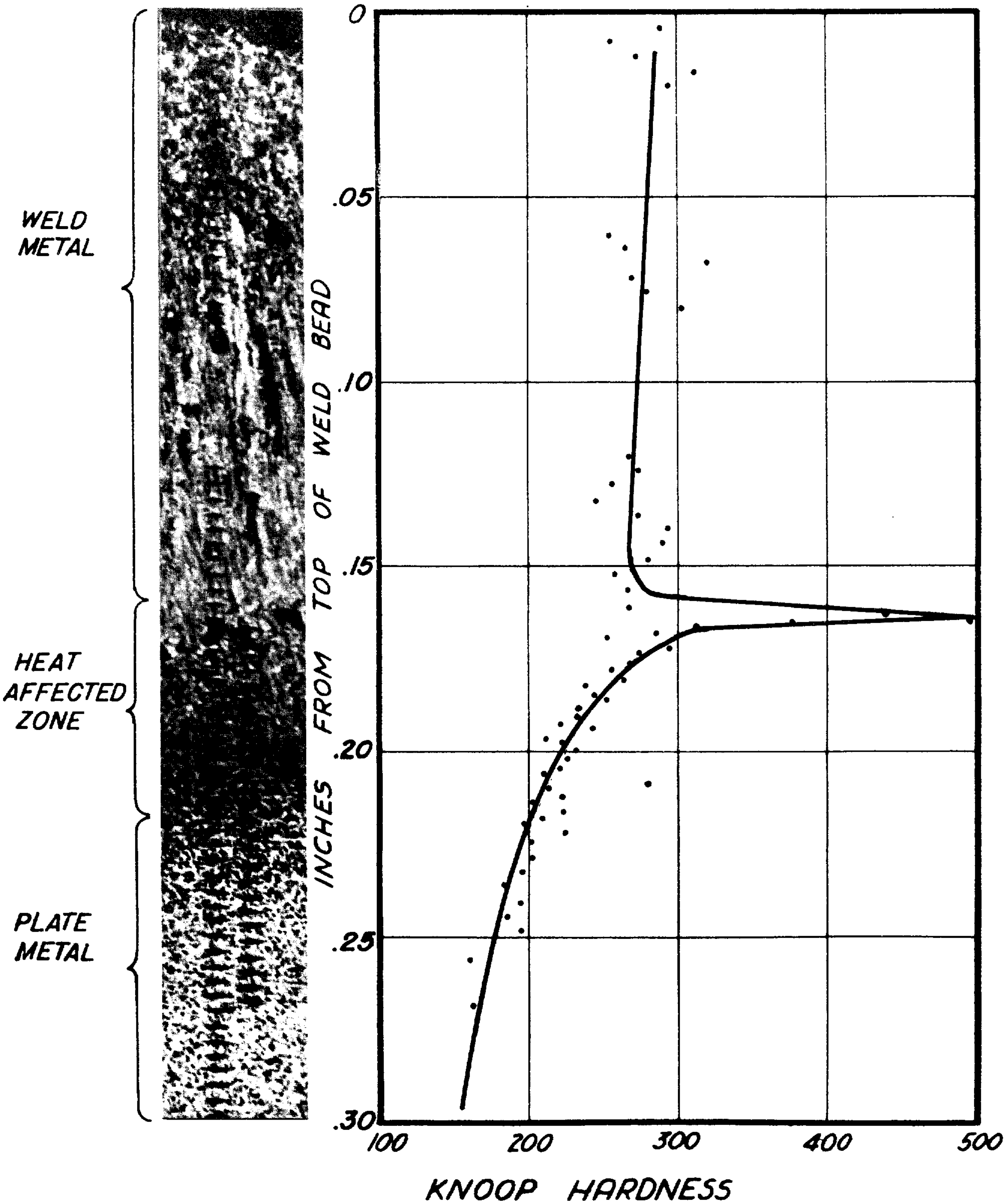


FIG. 42-SPECIMEN 76; SHIELDARC 85 ELECTRODE; 0 °F PREHEAT. (SEE TABLE 8)

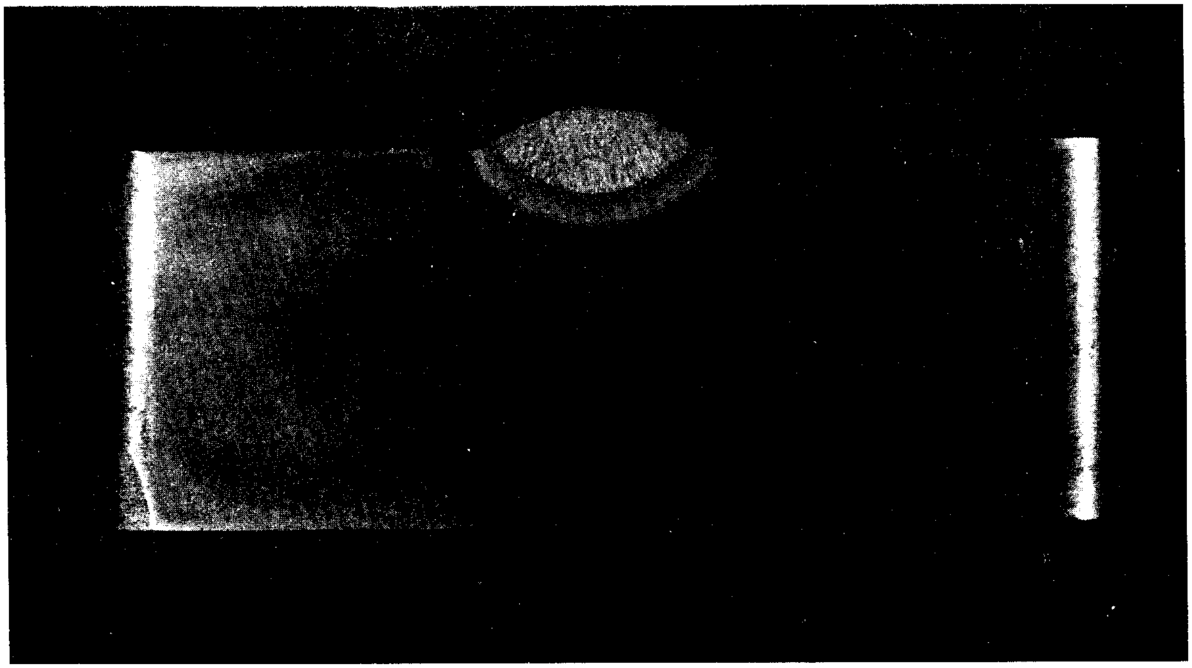


FIG. 43 · CROSS-SECTION OF WELD BEAD,
SPECIMEN 77 ($\frac{3}{4}$-INCH PLATE)

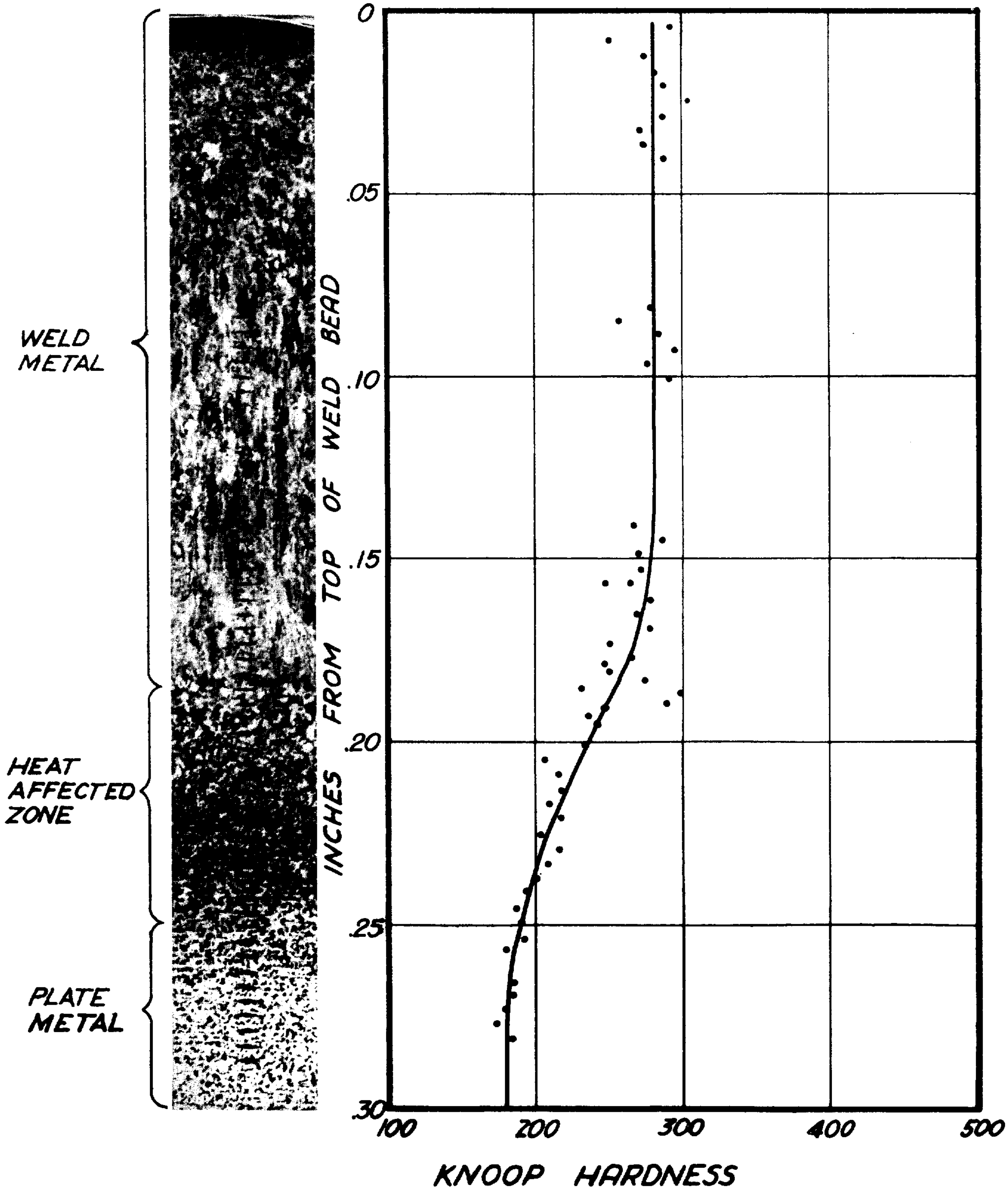


FIG. 44 - SPECIMEN 77; SHIELDARC 85 ELECTRODE; 100 °F PREHEAT. (SEE TABLE 8)

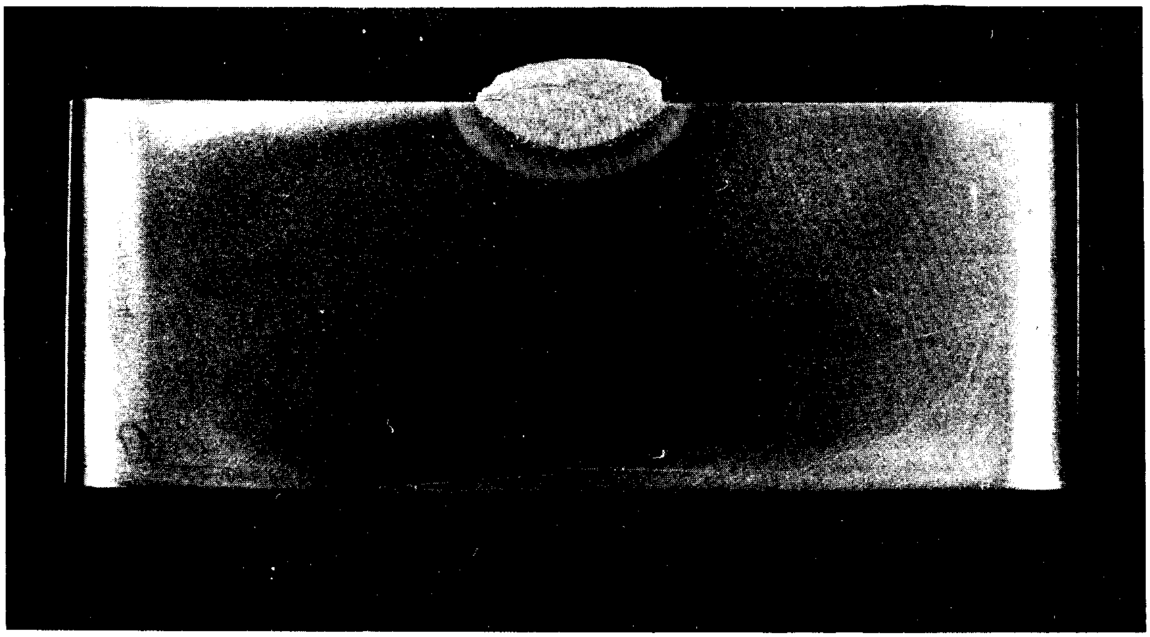


FIG. 45 - CROSS-SECTION OF WELD BEAD, SPECIMEN 78 ($\frac{3}{4}$ INCH PLATE)

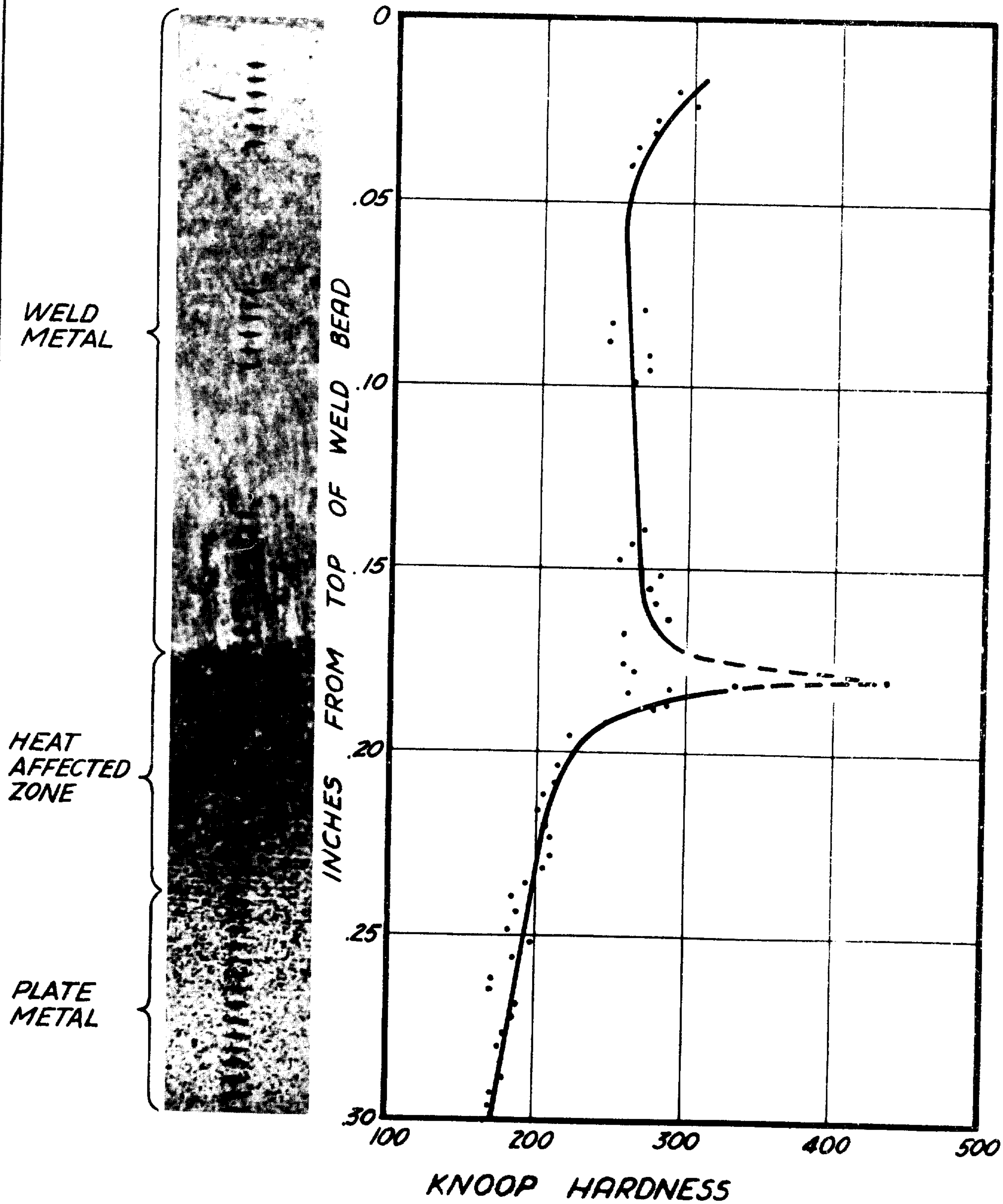


FIG. 46 - SPECIMEN 78; SHIELDARC 85 ELECTRODE; 200 °F PREHEAT. (SEE TABLE 8)

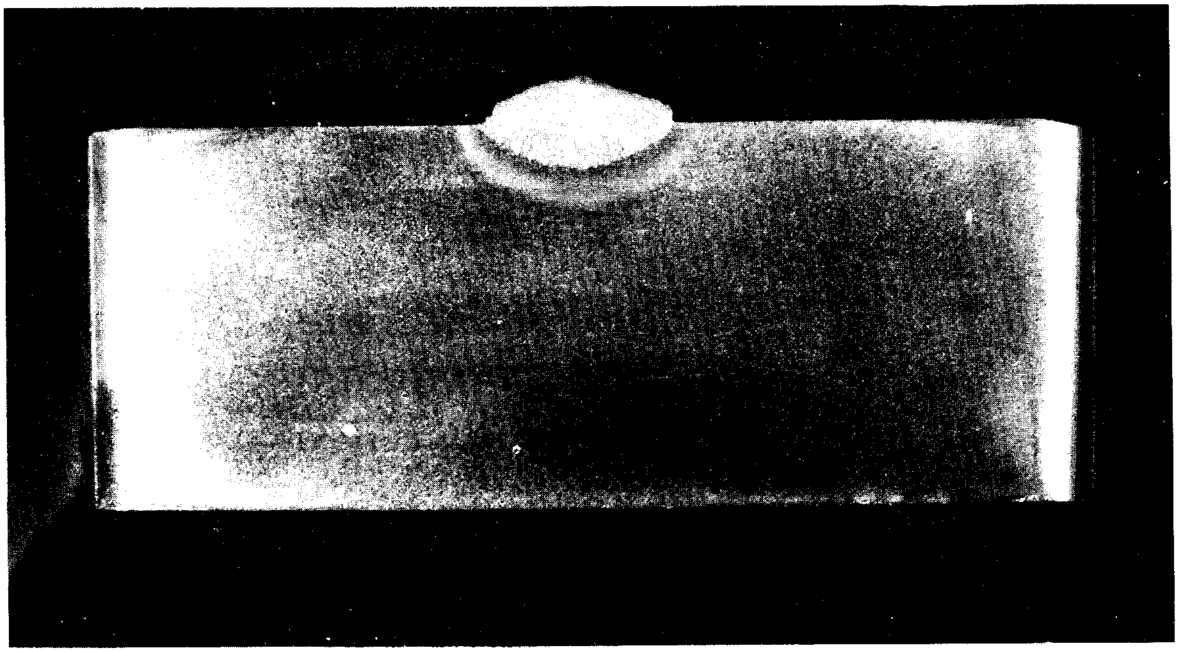


FIG. 47 - CROSS-SECTION OF WELD BEAD, SPECIMEN 79 ($\frac{3}{4}$ INCH PLATE)

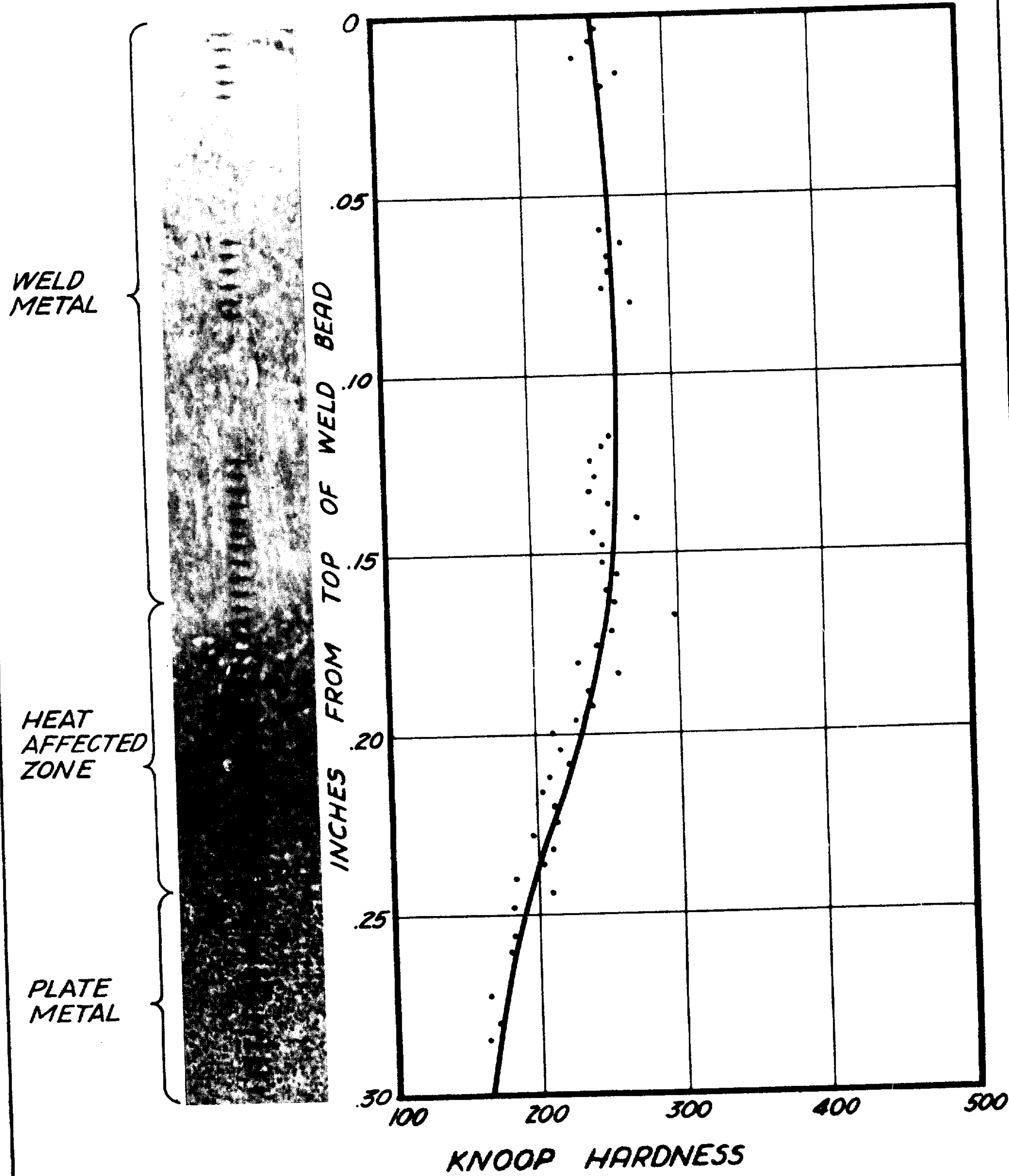


FIG. 48 - SPECIMEN 79; SHIELDARC 85 ELECTRODE; 300 °F PREHEAT. (SEE TABLE 8)

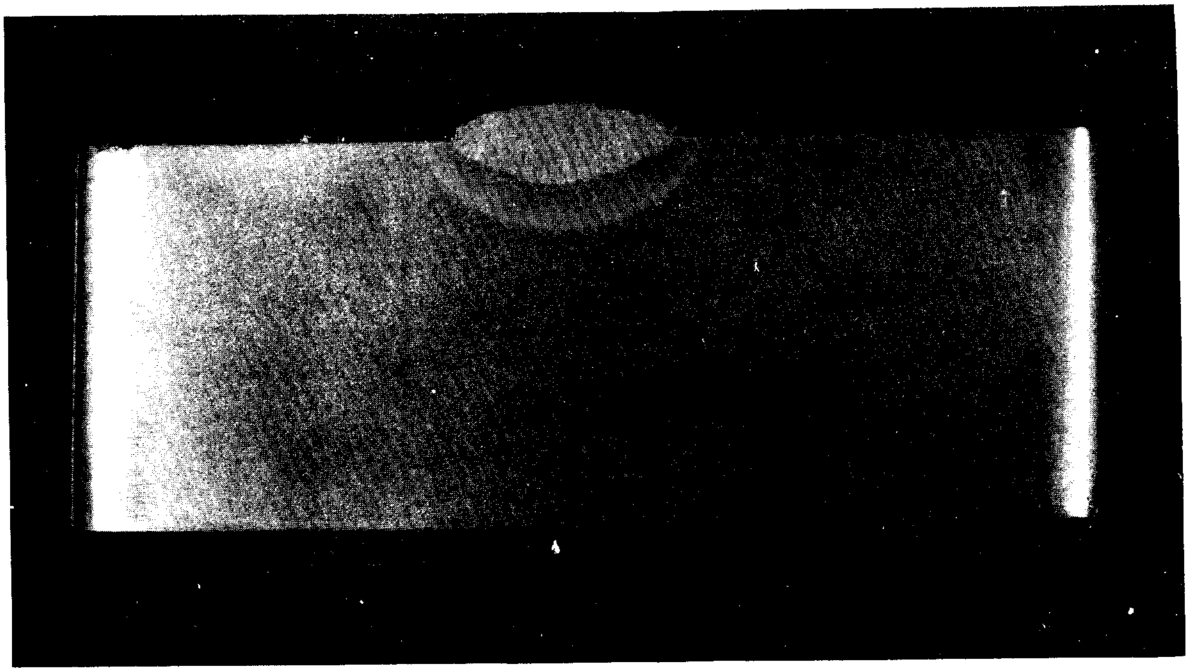


FIG. 49 - CROSS-SECTION OF WELD BEAD, SPECIMEN 80 ($\frac{3}{4}$ INCH PLATE)

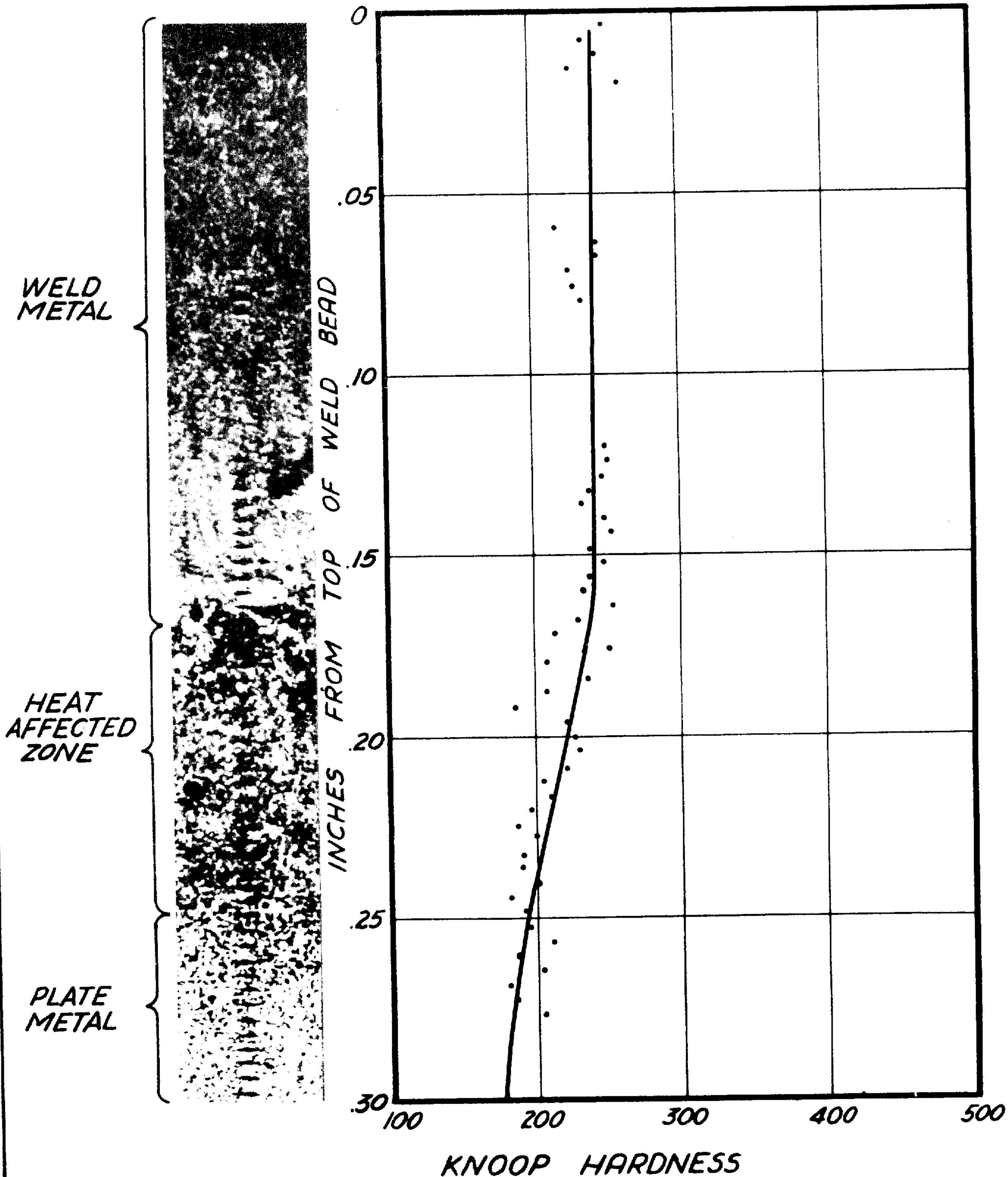


FIG. 50 - SPECIMEN 80; SHIELDARC 85 ELECTRODE; 400 °F PREHEAT. (SEE TABLE 8)

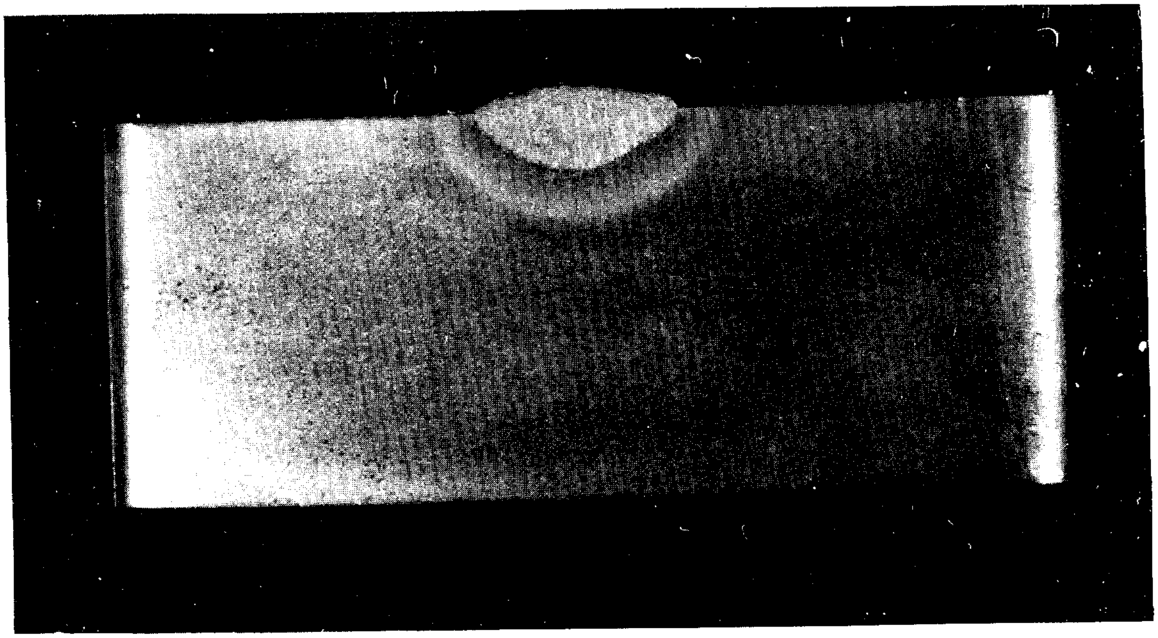


FIG. 51 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 81 ($\frac{3}{4}$-INCH PLATE)

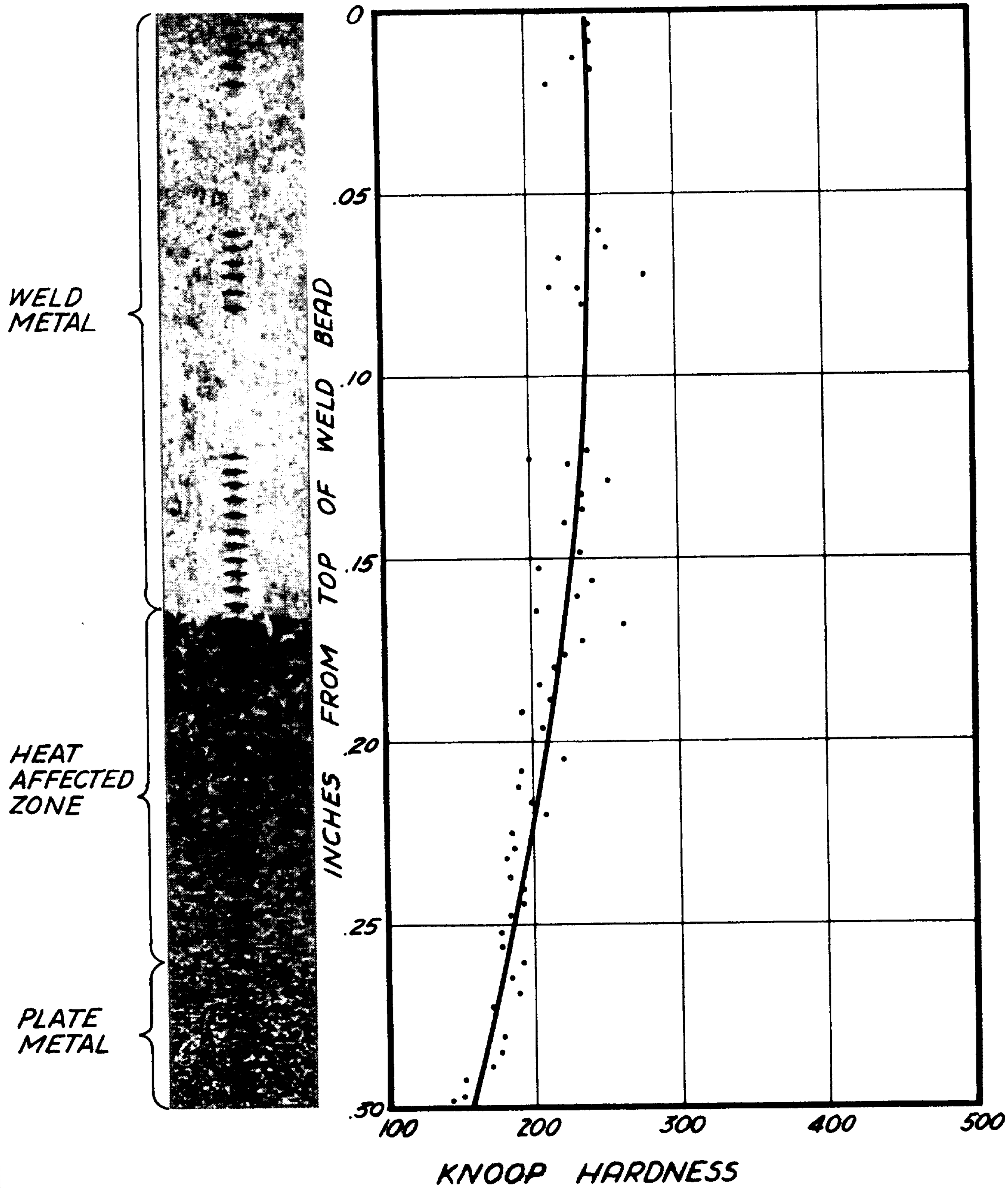


FIG. 52 - SPECIMEN 81; SHIELDARC 85 ELECTRODE; 500 °F PREHEAT. (SEE TABLE 8)

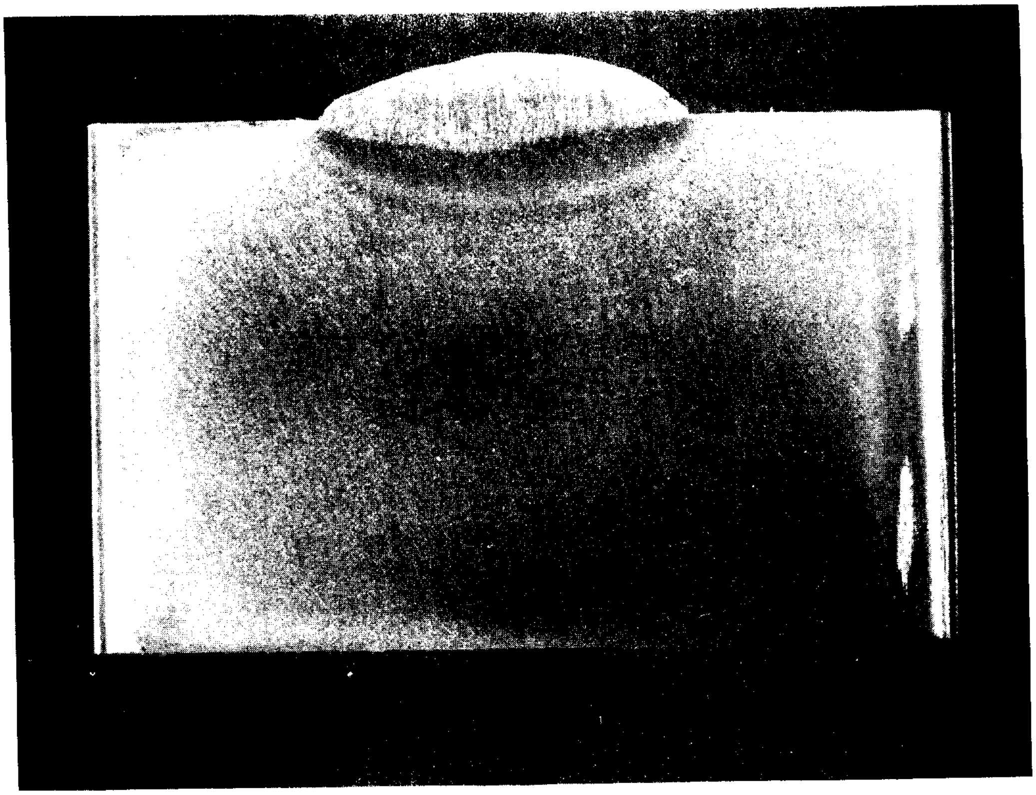


FIG. 53 - CROSS SECTION OF WELD BEAD,
SPECIMEN 82 ($\frac{3}{4}$-INCH PLATE)

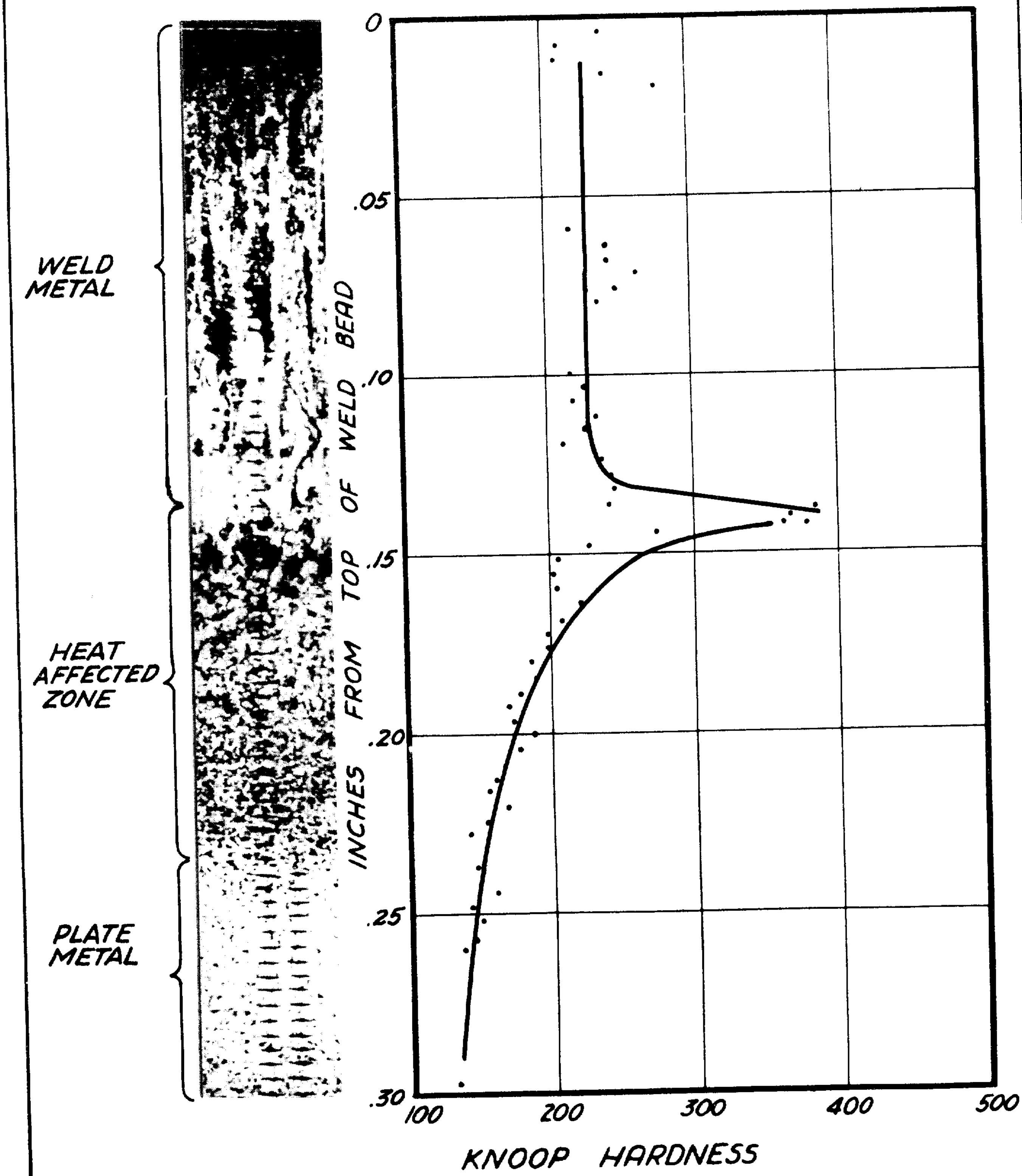


FIG. 54-SPECIMEN 82; UNIONMELT ELECTRODE; 0 °F PREHEAT. (SEE TABLE 8)

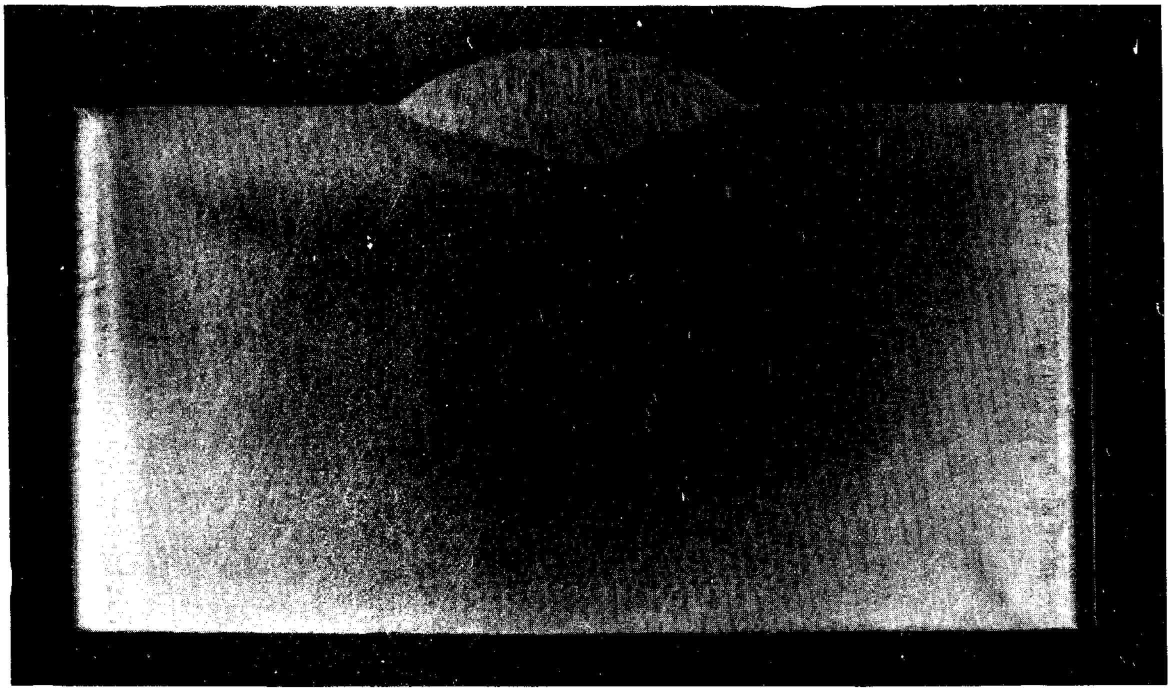


FIG. 55 CROSS SECTION OF WELD BEAD, SPECIMEN 83 ($\frac{3}{4}$-INCH PLATE)

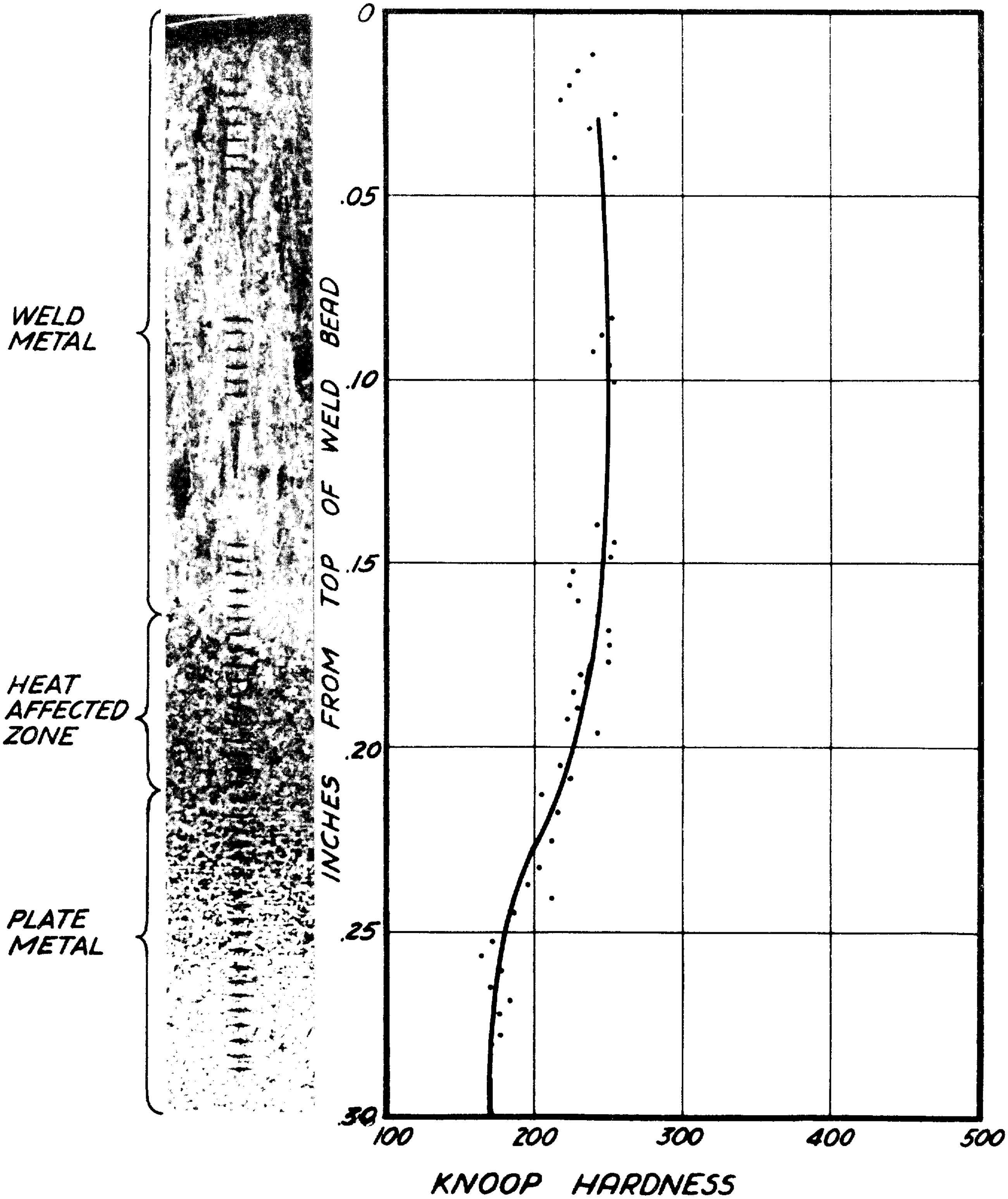


FIG. 56-SPECIMEN 83; UNIONMELT ELECTRODE; 100°F PREHEAT. (SEE TABLE 8)

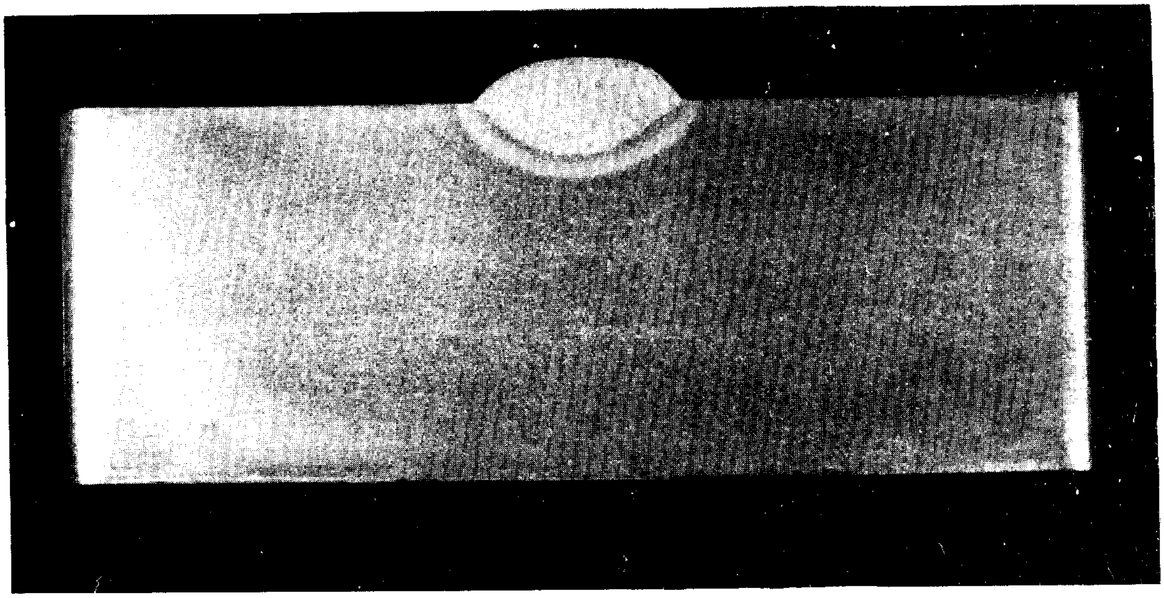


FIG. 57 - CROSS-SECTION OF WELD BEAD, SPECIMEN 84 ($\frac{3}{4}$ INCH PLATE)

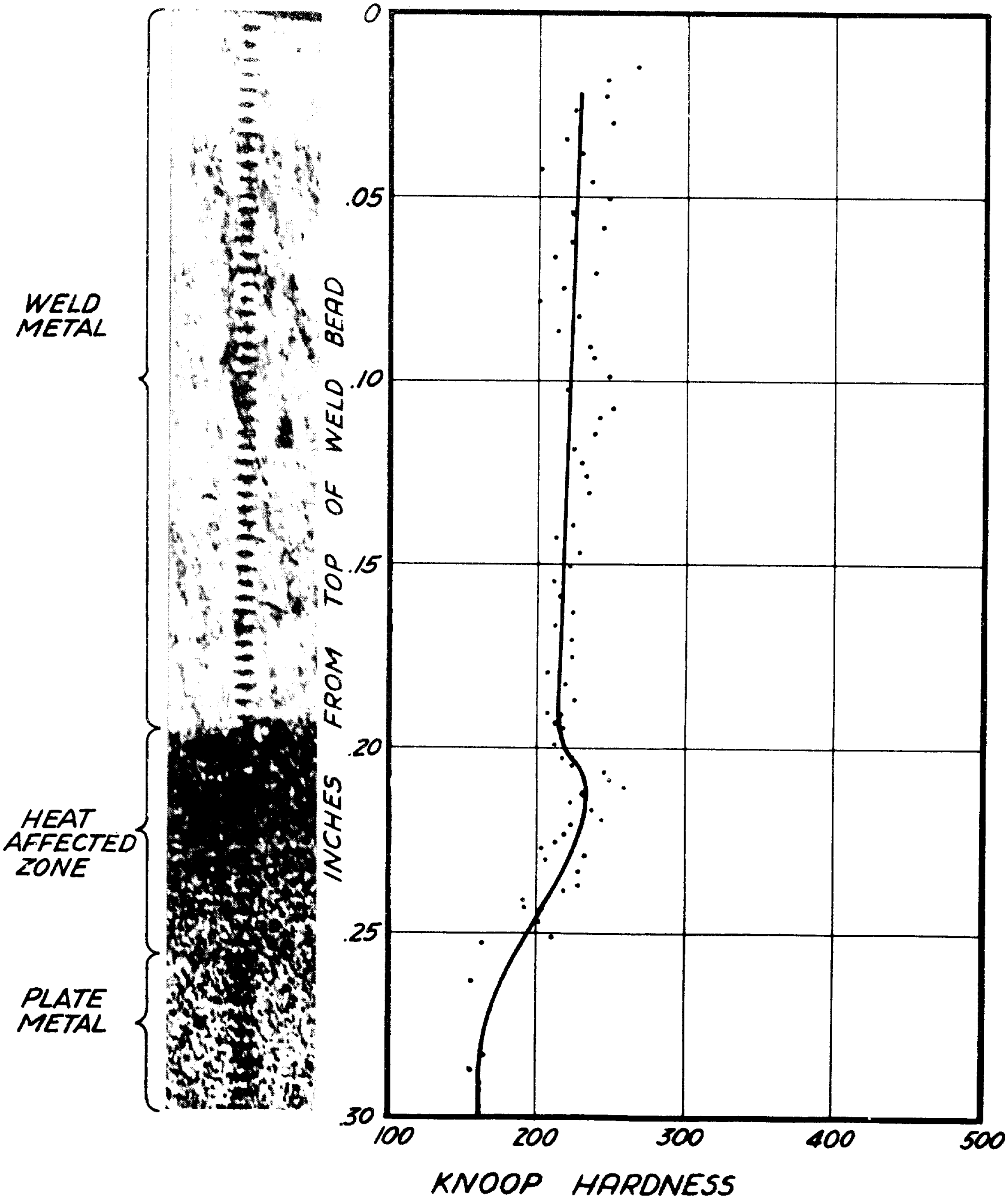


FIG. 58-SPECIMEN 84; UNIONMELT 5 ELECTRODE; 200 °F PREHEAT. (SEE TABLE 8)

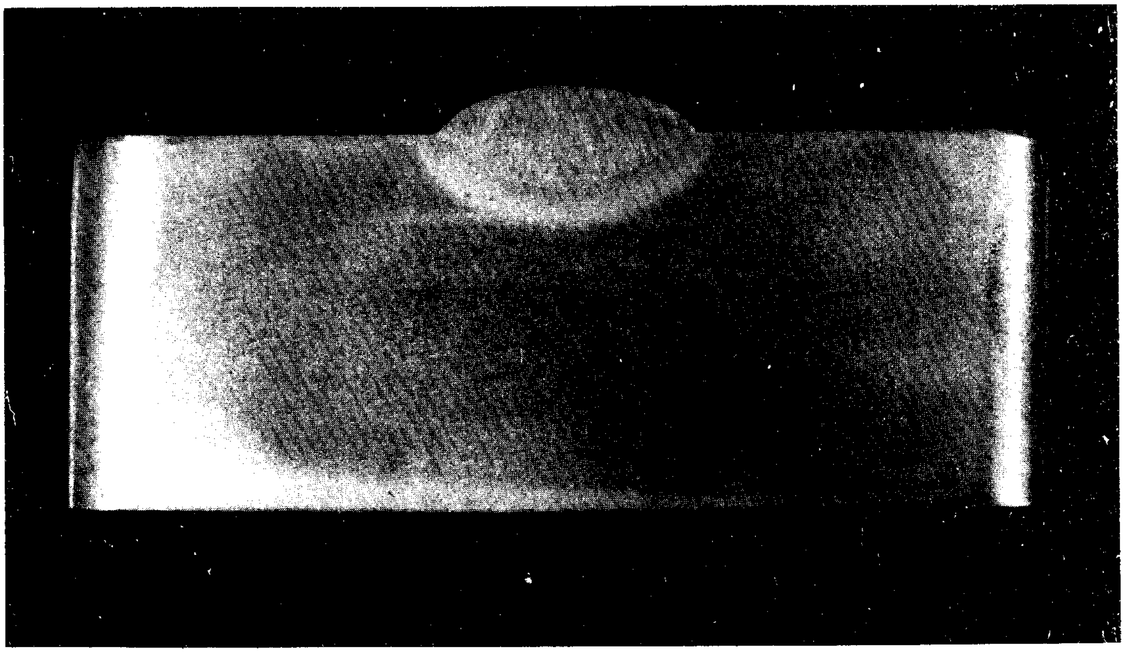


FIG. 59 - CROSS-SECTION OF WELD BEAD, SPECIMEN 85 ($\frac{3}{4}$-INCH PLATE)

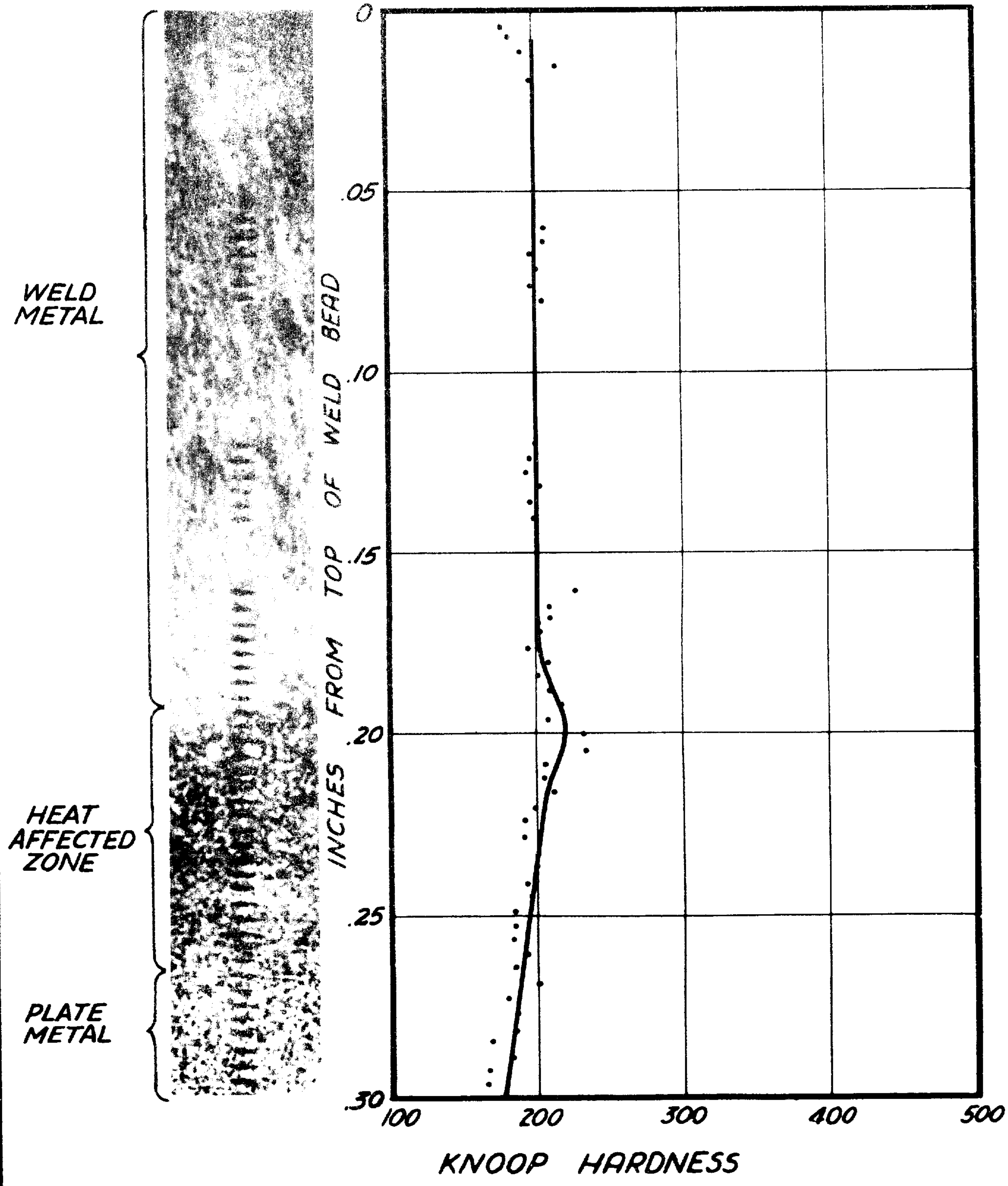


FIG. 60 - SPECIMEN 85; UNIONMELT ELECTRODE; 300°F PREHEAT. (SEE TABLE 8)

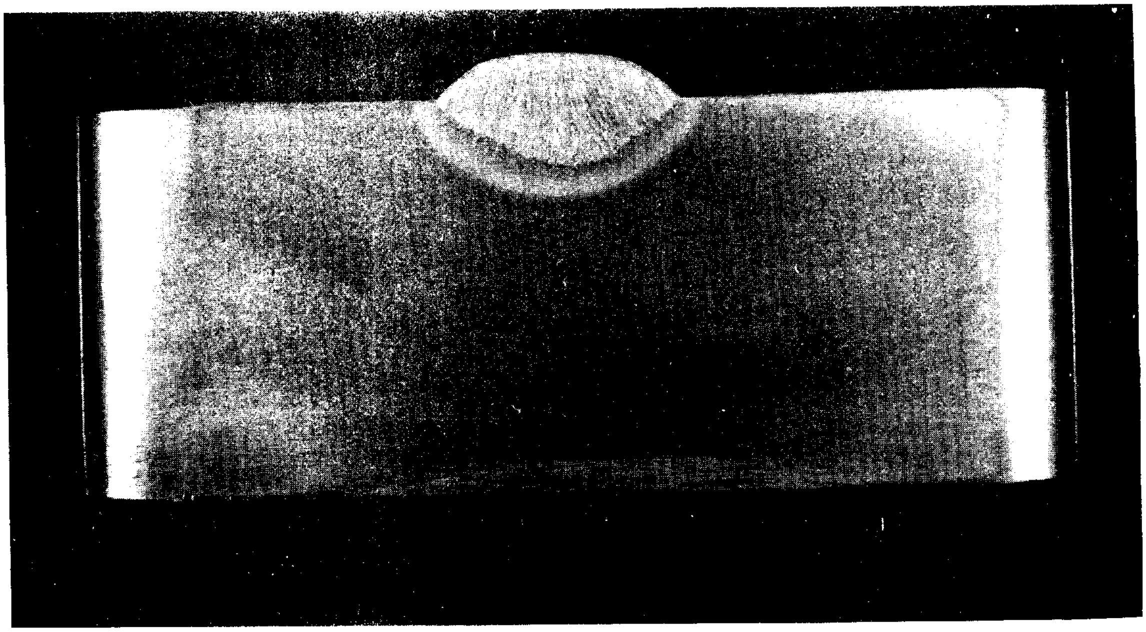


FIG. 61 - CROSS SECTION OF WELD BEAD, SPECIMEN 86 ($\frac{3}{4}$-INCH PLATE)

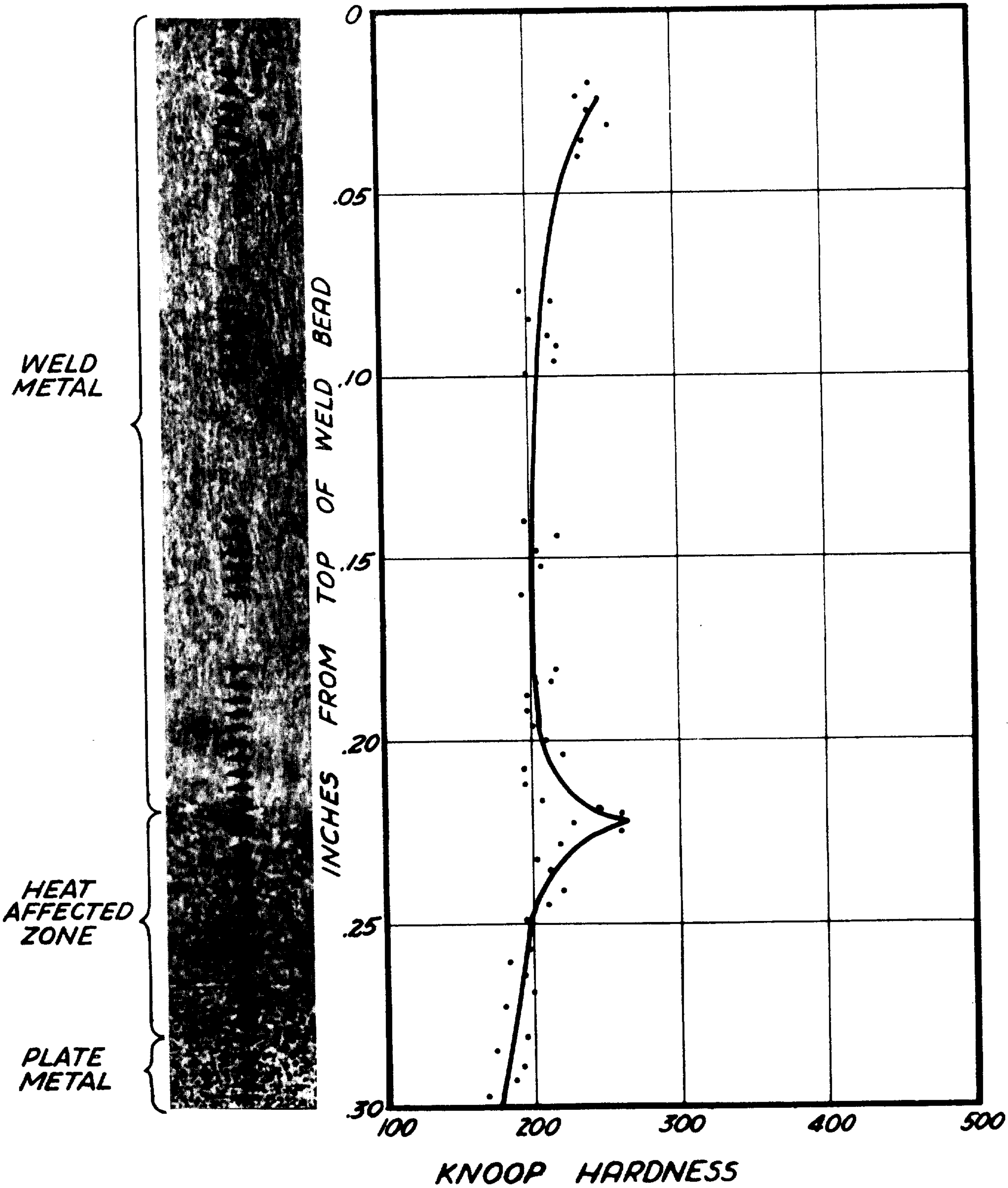


FIG. 62 - SPECIMEN 86; UNIONMELT ELECTRODE; 400°F PREHEAT. (SEE TABLE 8)

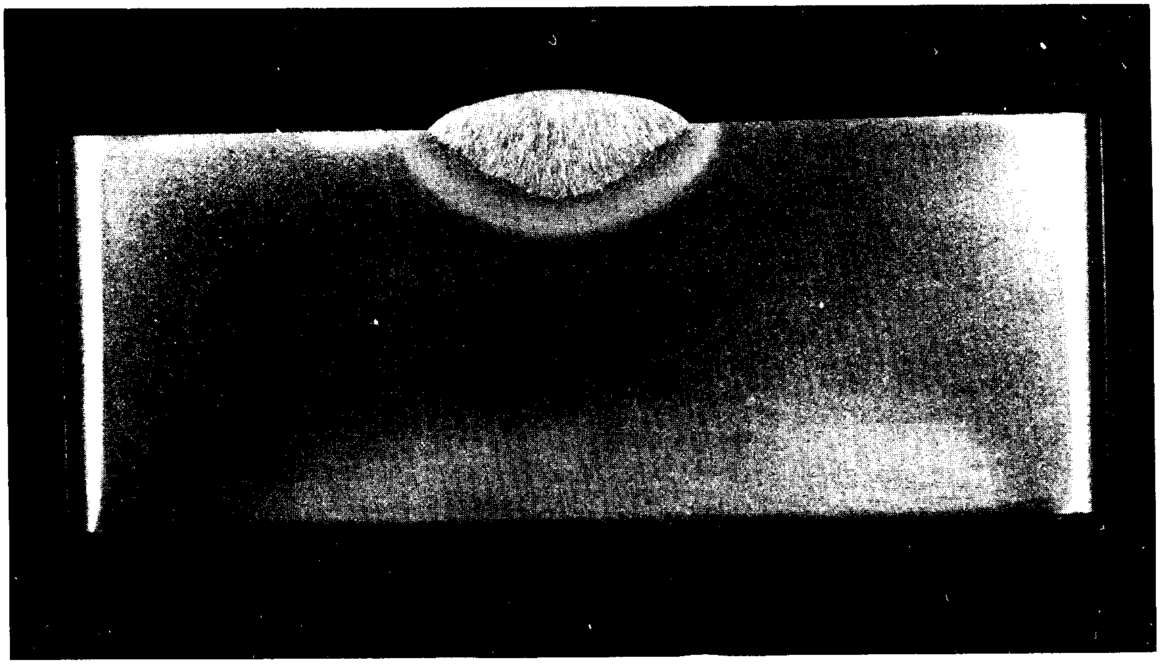


FIG. 63 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 87 ($\frac{3}{4}$-INCH PLATE)

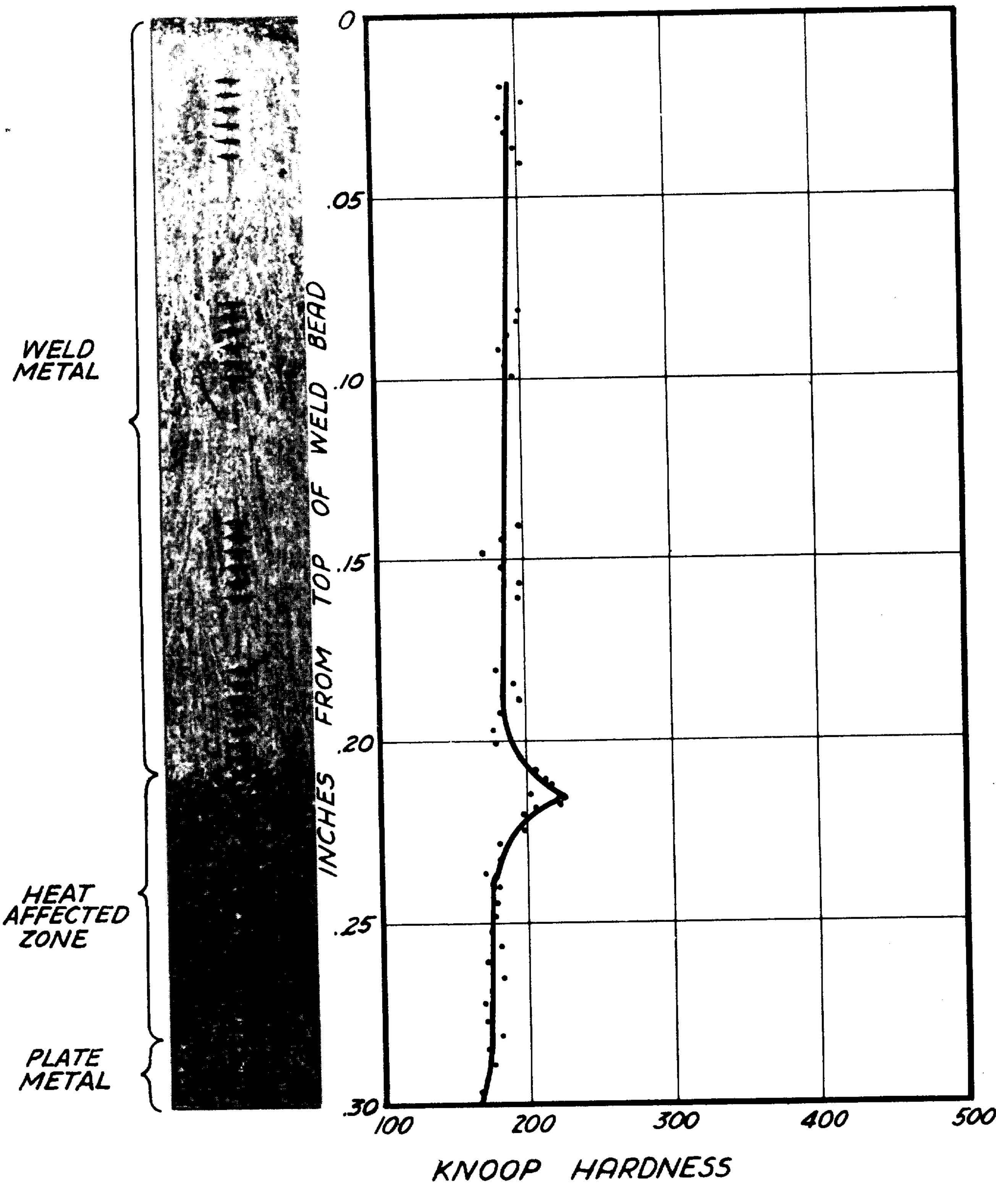


FIG. 64 - SPECIMEN 87; UNIONMELT ELECTRODE; 500°F PREHEAT. (SEE TABLE 8)

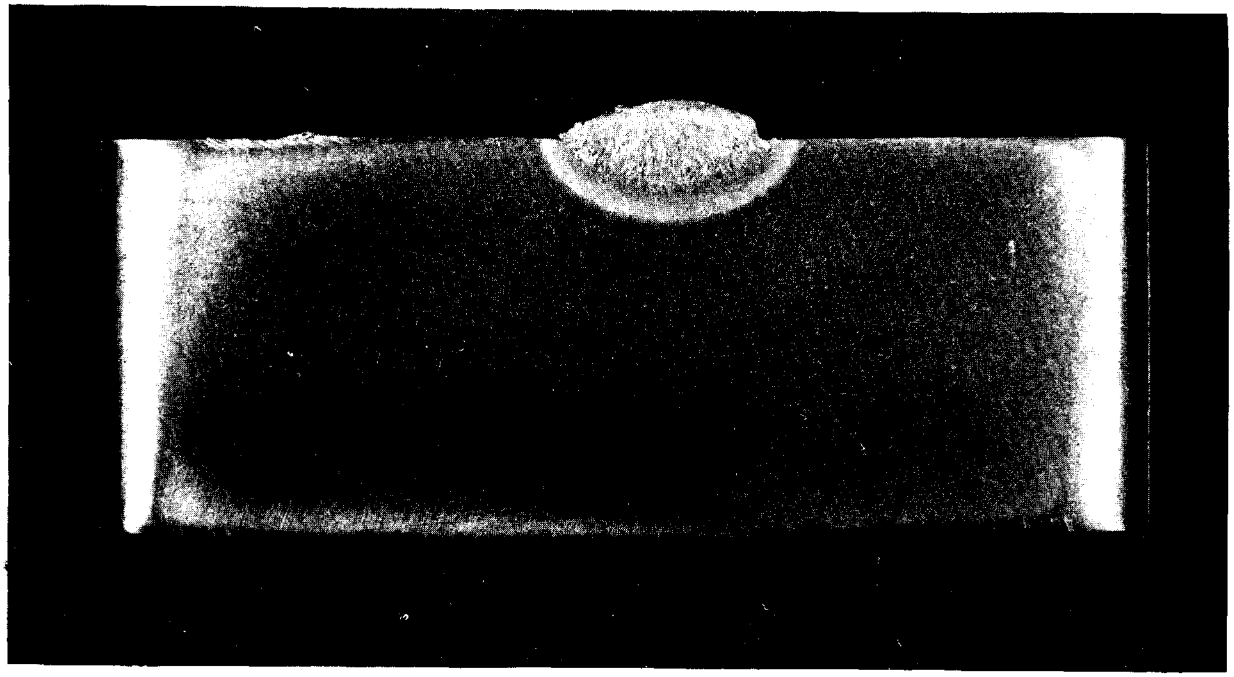


FIG. 65 - CROSS-SECTION OF WELD BEAD, SPECIMEN 88 ($\frac{3}{4}$-INCH PLATE)

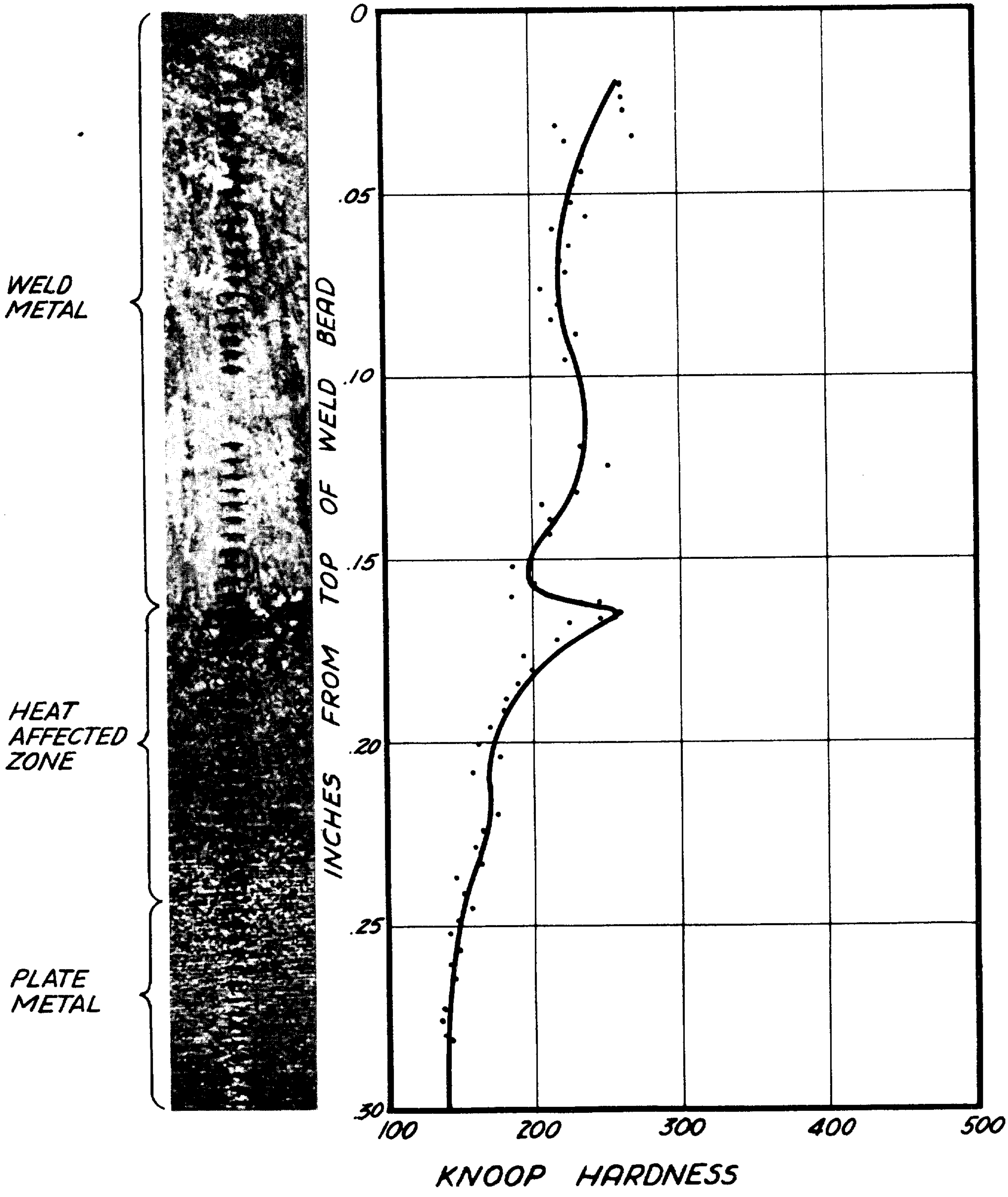


FIG.66 - SPECIMEN 88; FLEETWELD 5 ELECTRODE; 1 HOUR - 1100°F POSTHEAT. (SEE TABLE 8)

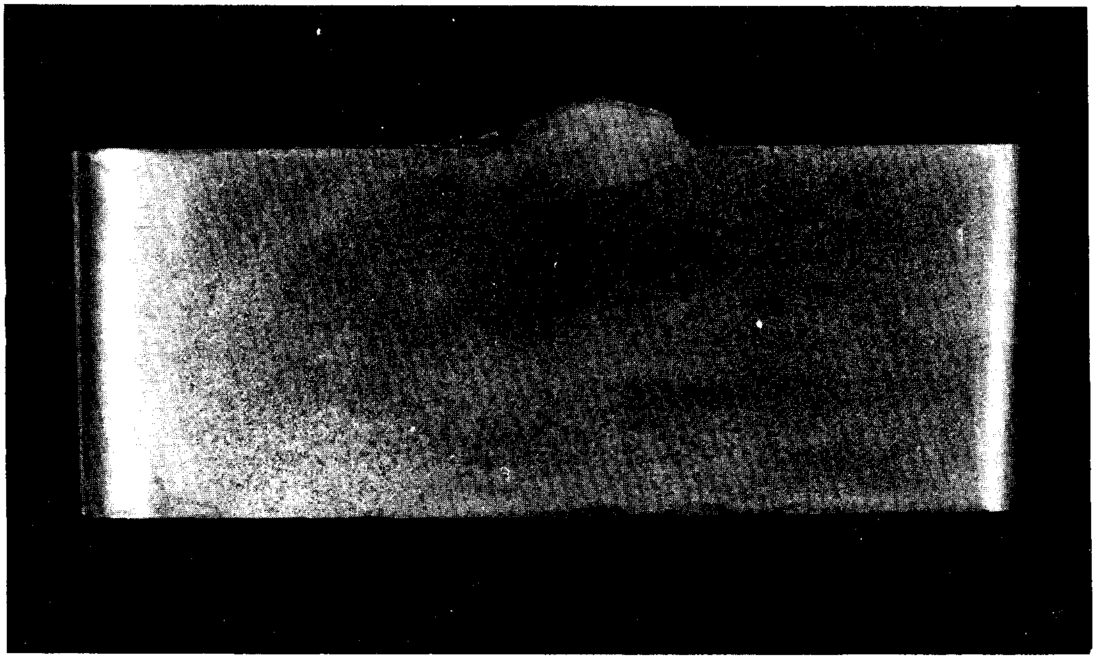


FIG. 67 - CROSS-SECTION OF WELD BEAD, SPECIMEN 89 ($\frac{3}{4}$-INCH PLATE)

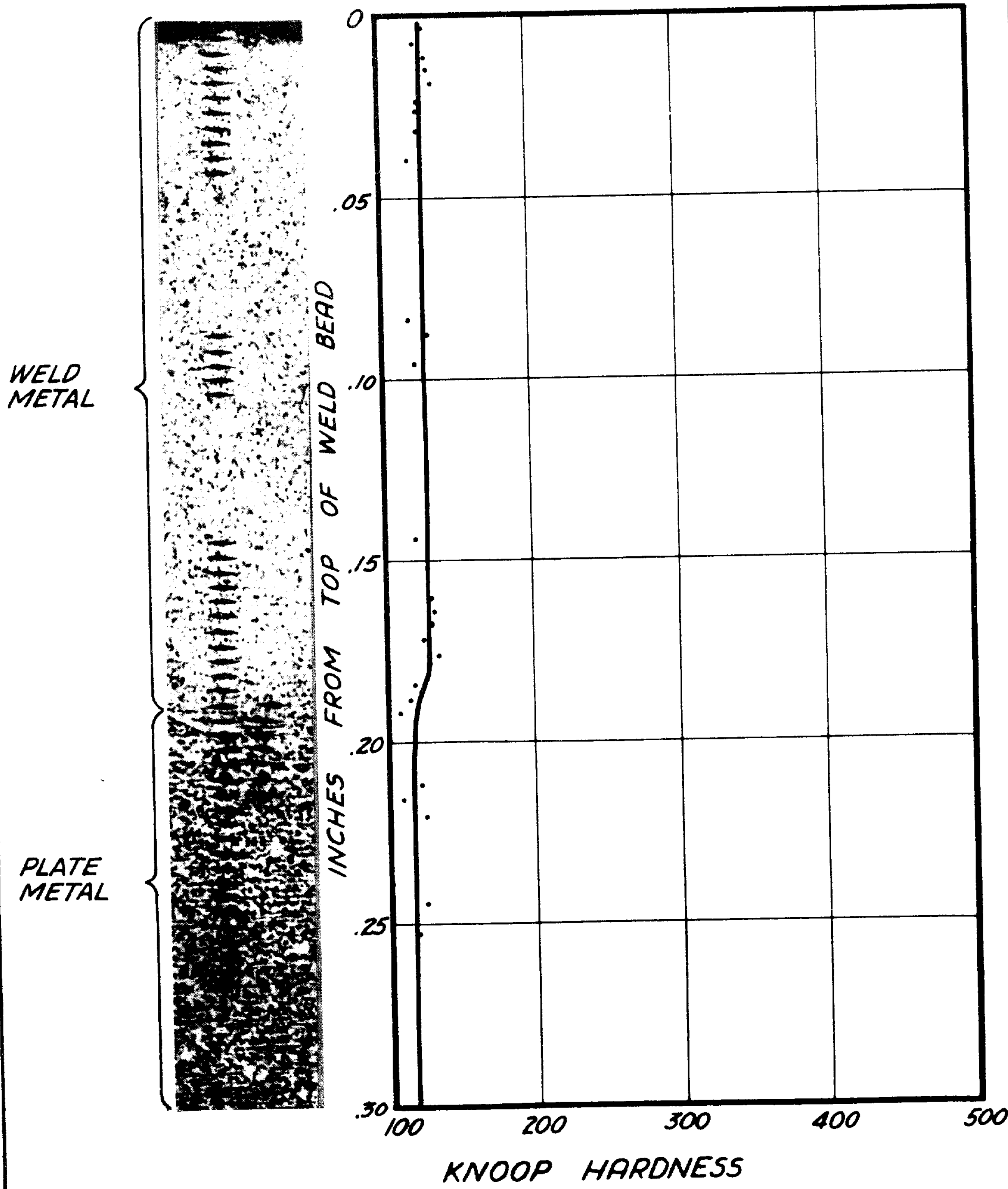


FIG. 68 - SPECIMEN 89; FLEETWELD 5 ELECTRODE; $\frac{3}{4}$ HOUR - 1650°F POSTHEAT. (SEE TABLE 8)

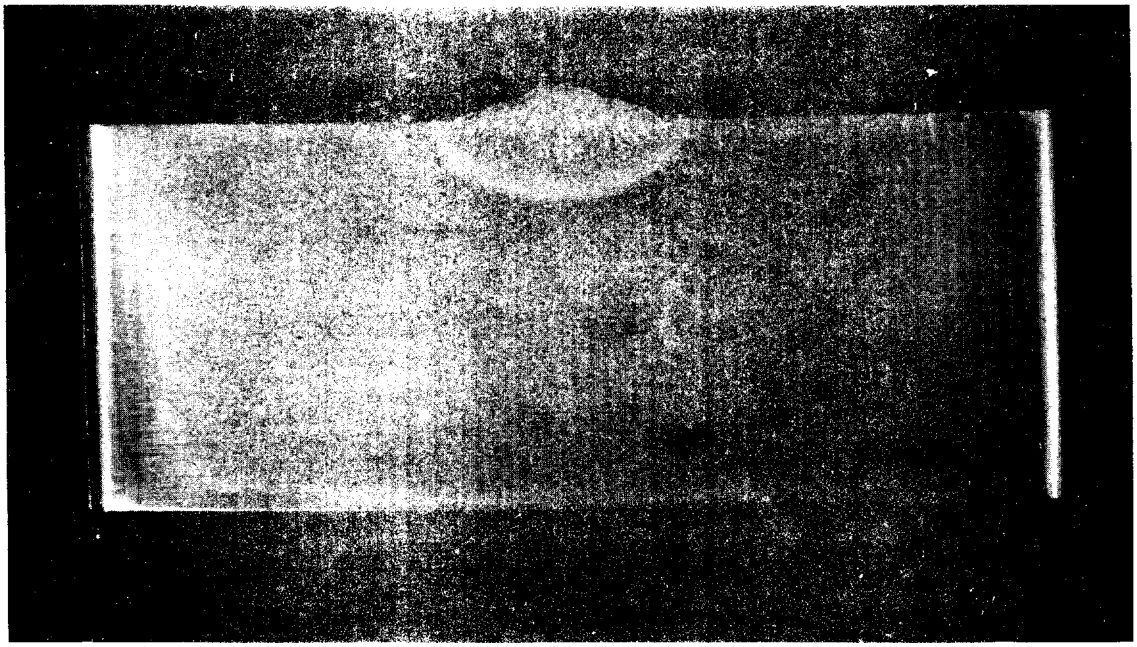


FIG. 69 [illegible] BEAD,
[illegible] PLATE)

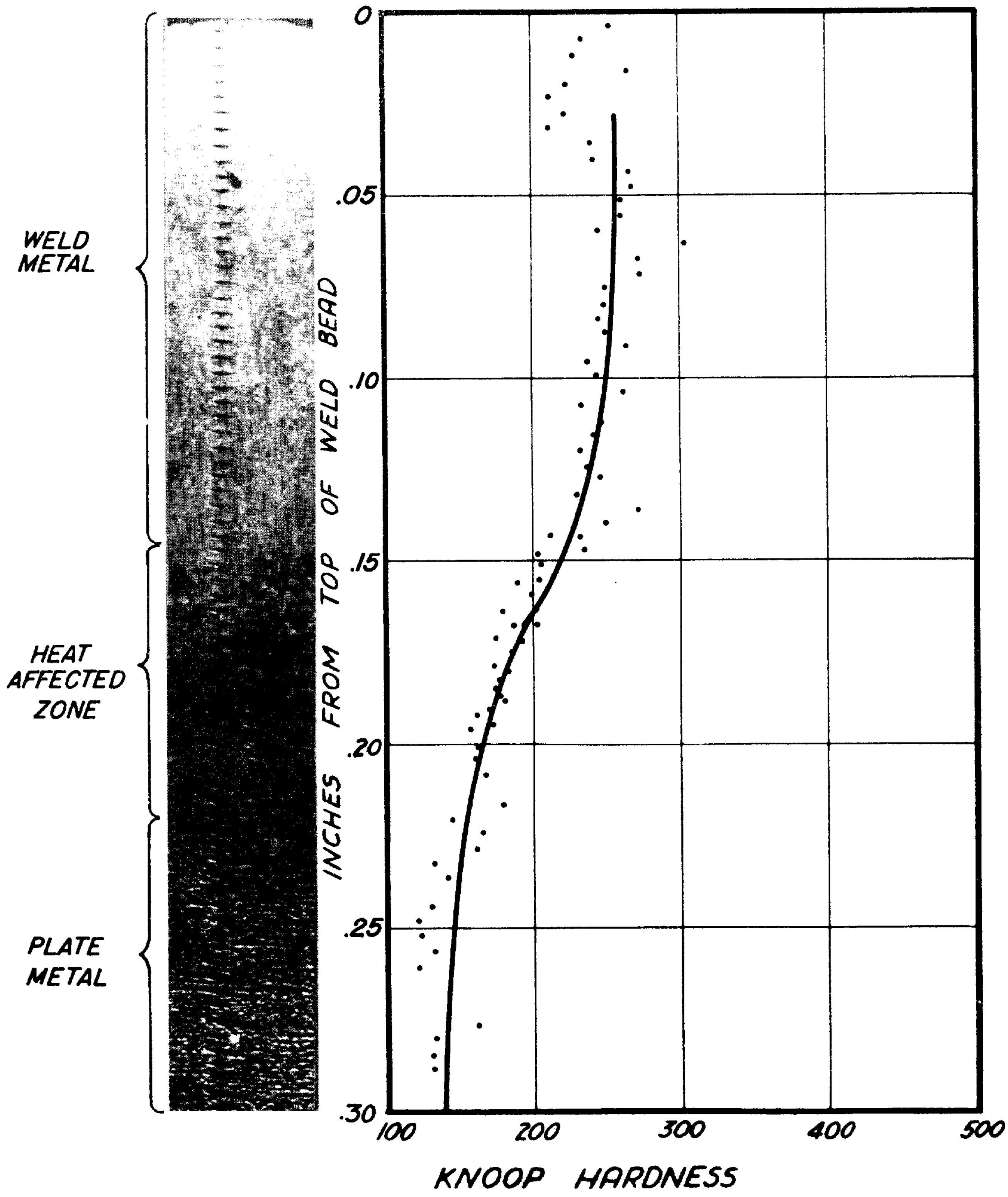


FIG. 70 - SPECIMEN 90; SHIELDARC 85 ELECTRODE; 1 HOUR - 1100 °F POSTHEAT. (SEE TABLE 8)

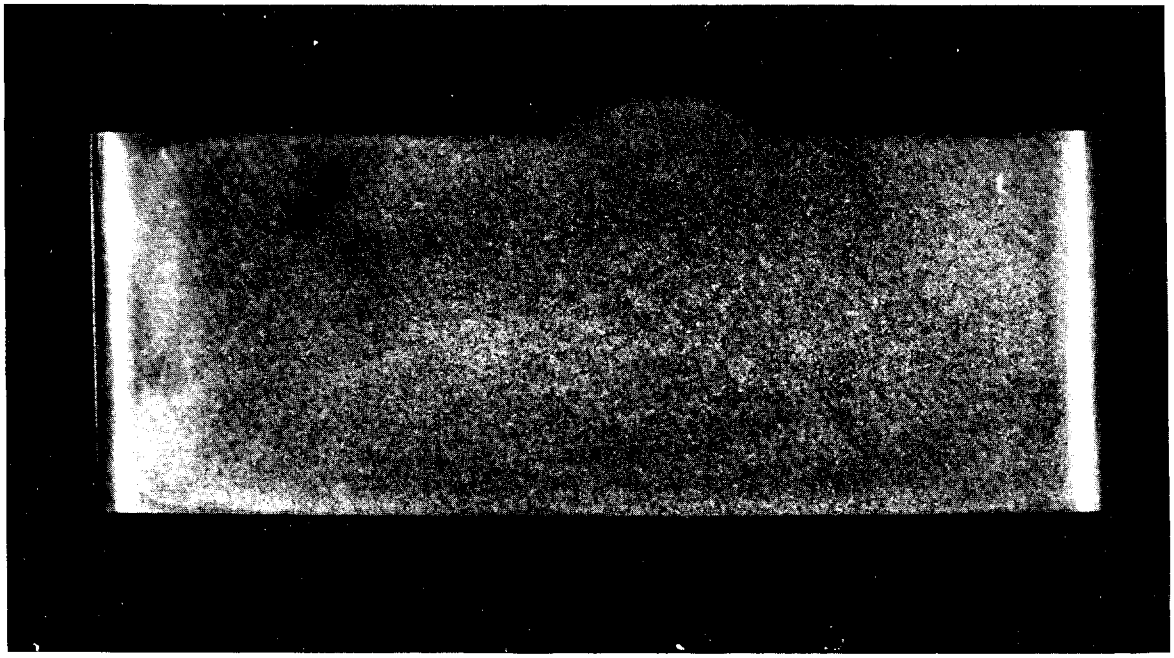


FIG. 71 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 91 ($\frac{3}{4}$-INCH PLATE)

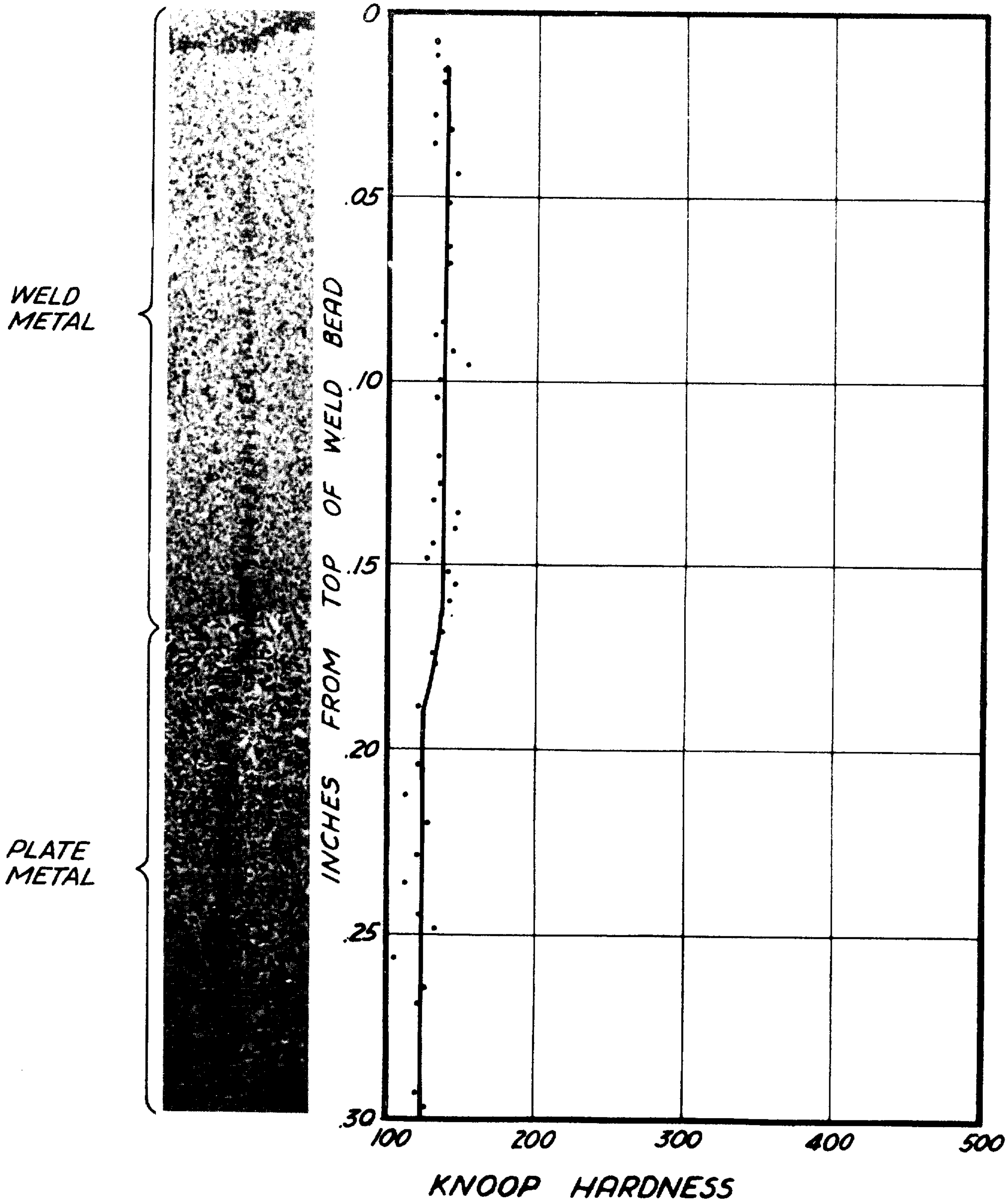


FIG. 72 · SPECIMEN 91; SHIELDARC 85 ELECTRODE; ¾ HOUR - 1650 °F POSTHEAT. (SEE TABLE 8)

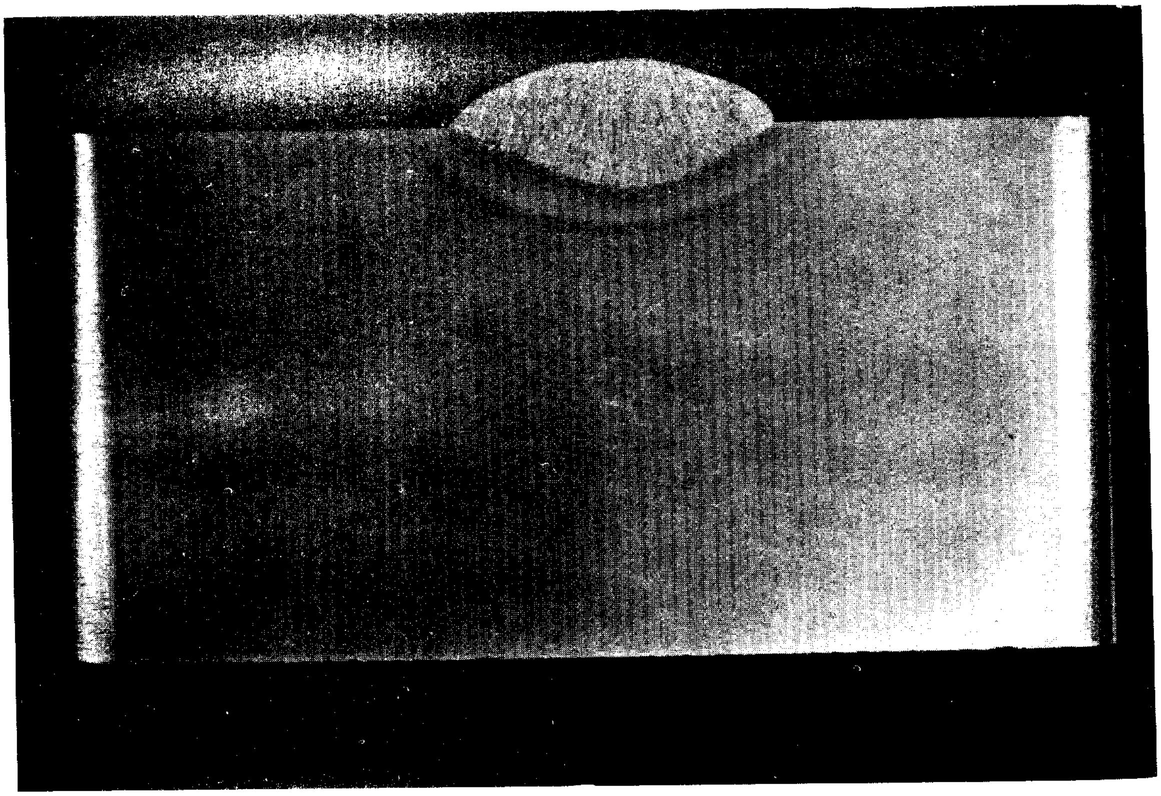


FIG. 73 - CROSS-SECTION OF WELD BEAD, SPECIMEN 94 ($\frac{3}{4}$-INCH PLATE)

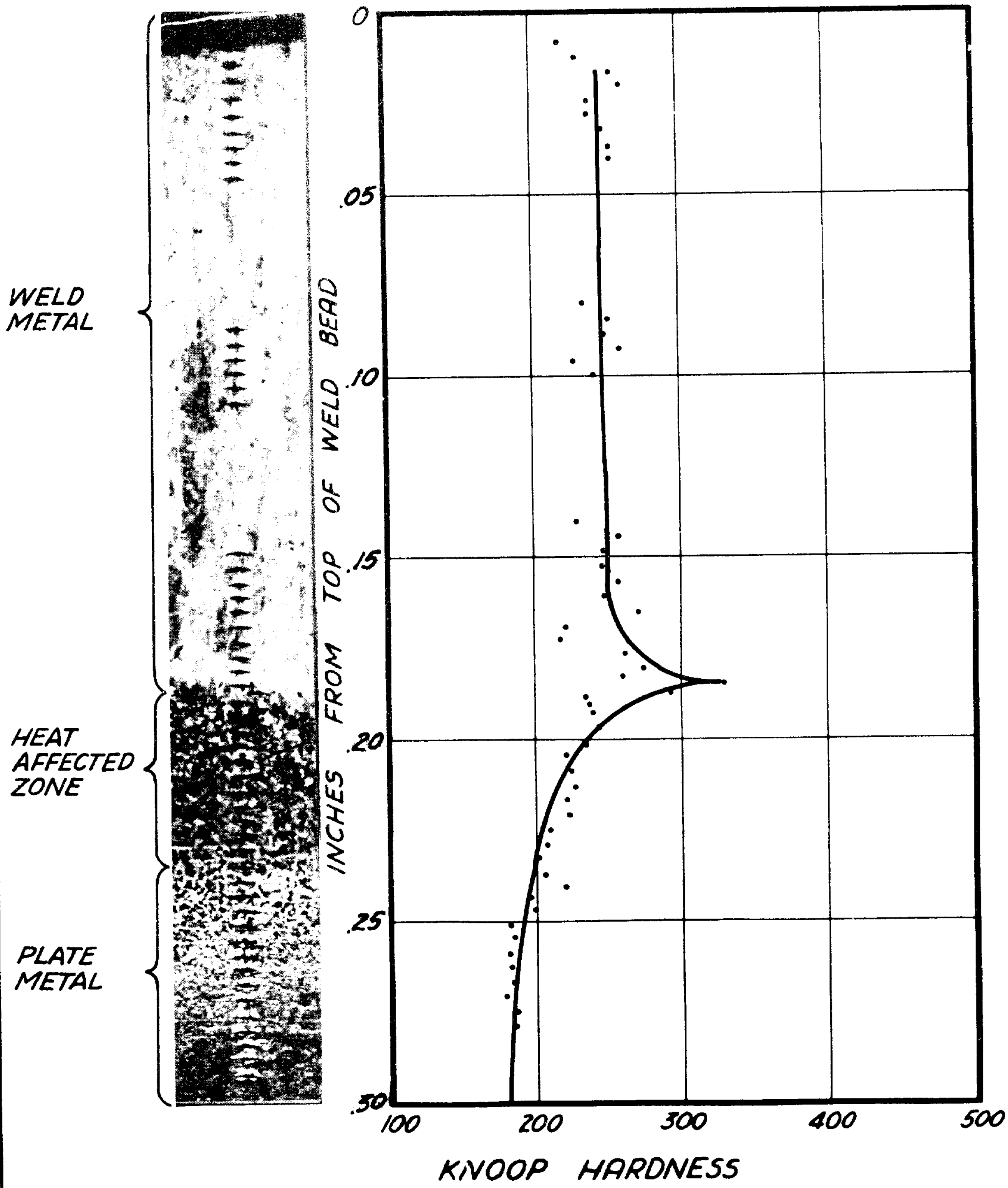


FIG. 74 -SPECIMEN 94; UNIONMELT ELECTRODE; 0°F PREHEAT (SEE TABLE 9)

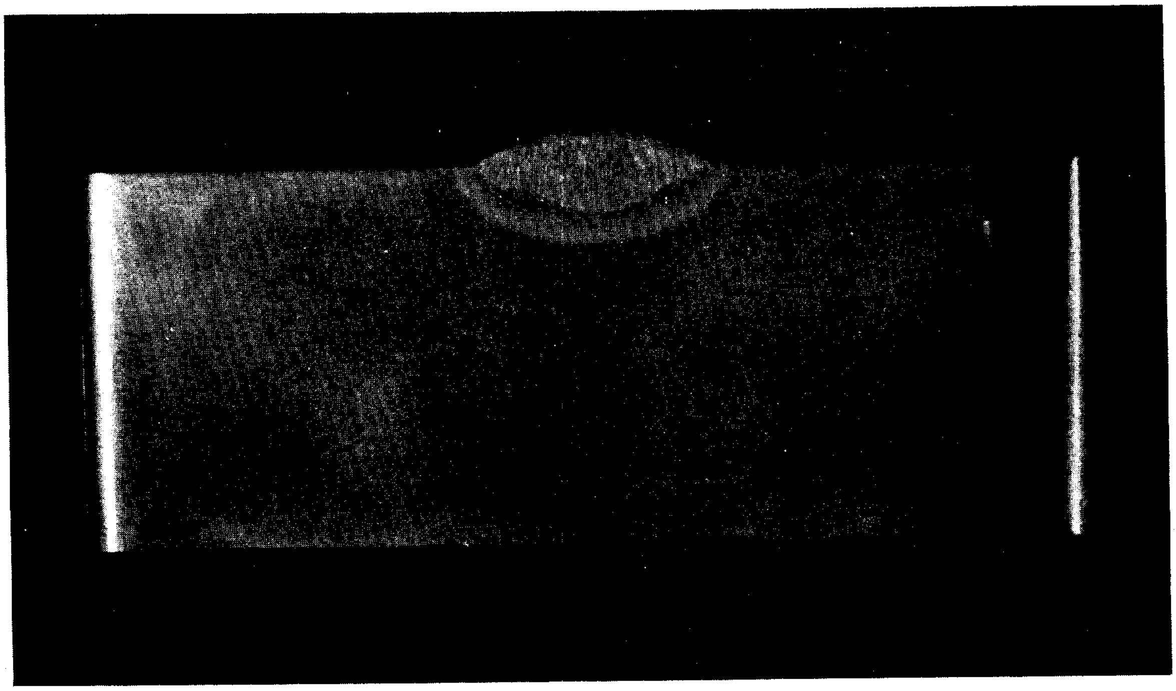


FIG. 75 - CROSS-SECTION OF WELD BEAD, SPECIMEN 95 ($\frac{3}{4}$-INCH PLATE)

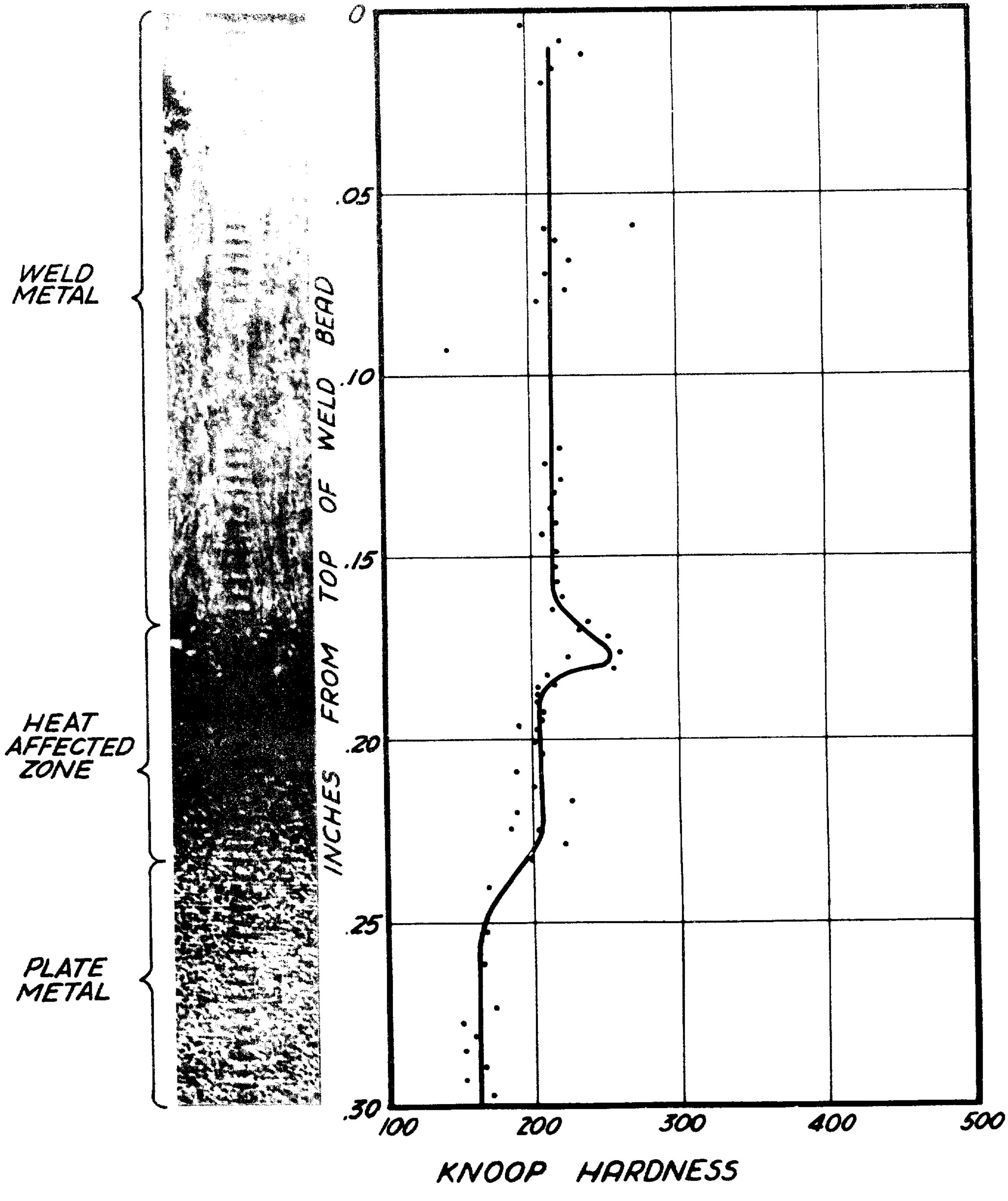


FIG. 76 - SPECIMEN 95; UNIONMELT ELECTRODE; 100°F PREHEAT. (SEE TABLE 9)

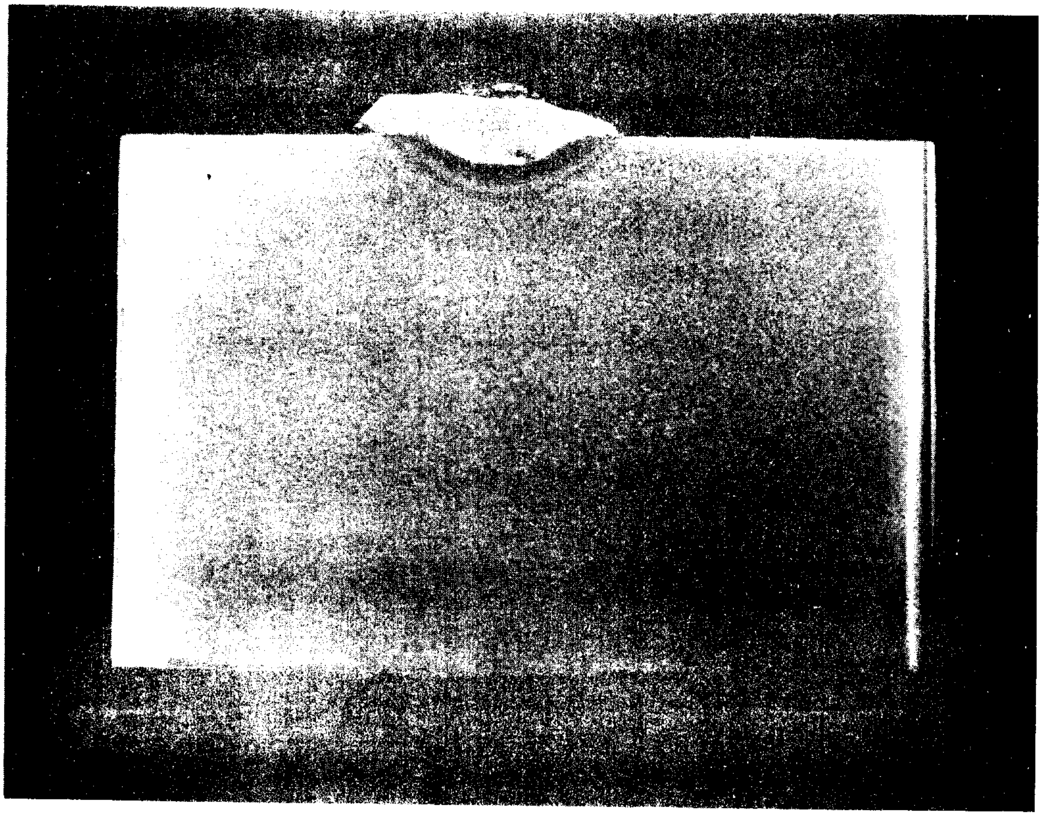


FIG. 77 CROS[illegible] W[illegible] BEAD,
SPECIMEN [illegible]OO [illegible] ($\frac{3}{4}$-INCH PLATE)

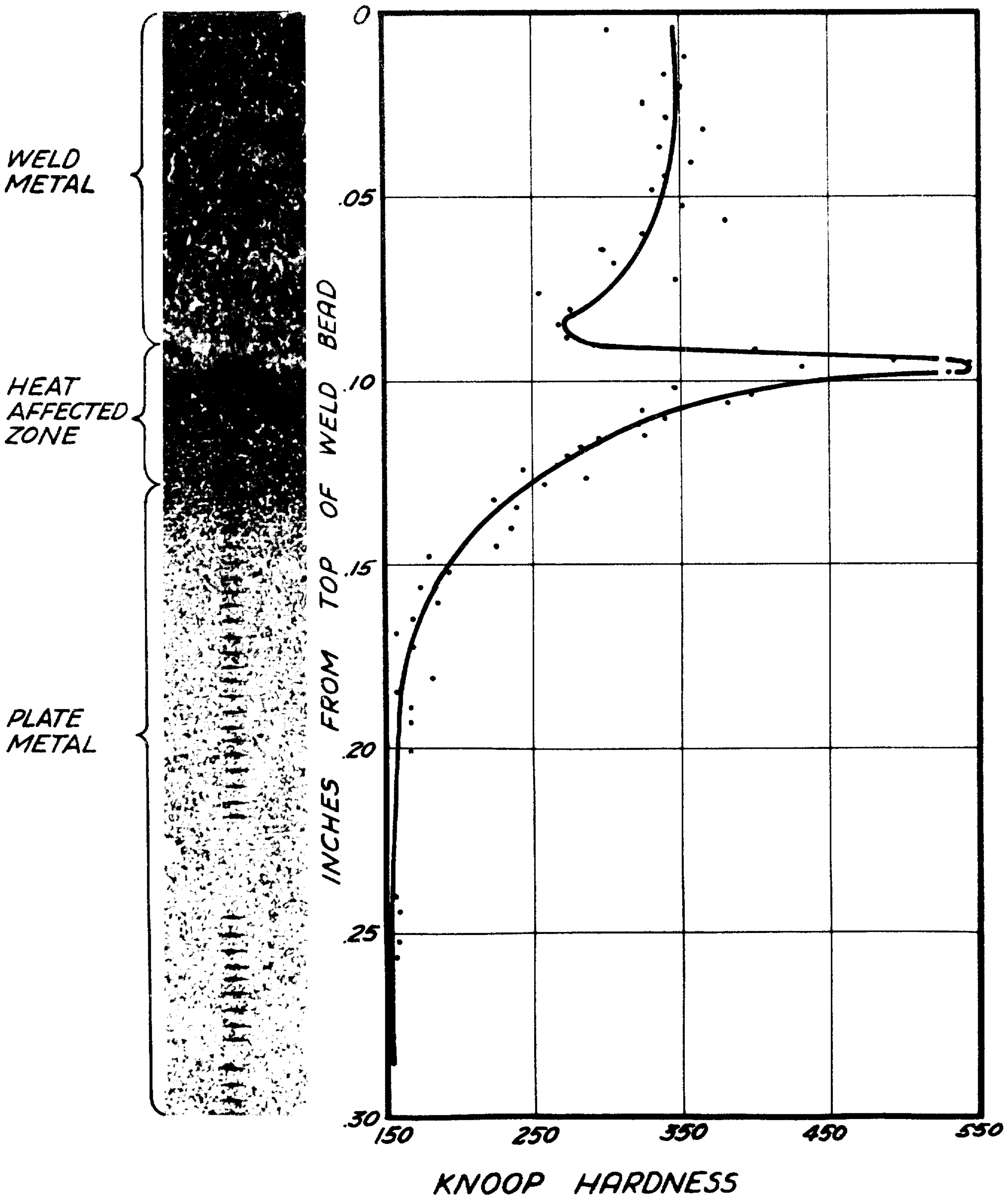


FIG. 7B -SPECIMEN 100; FLEETWELD 5 ELECTRODE; 0 °F PREHEAT. (SEE TABLE 9)

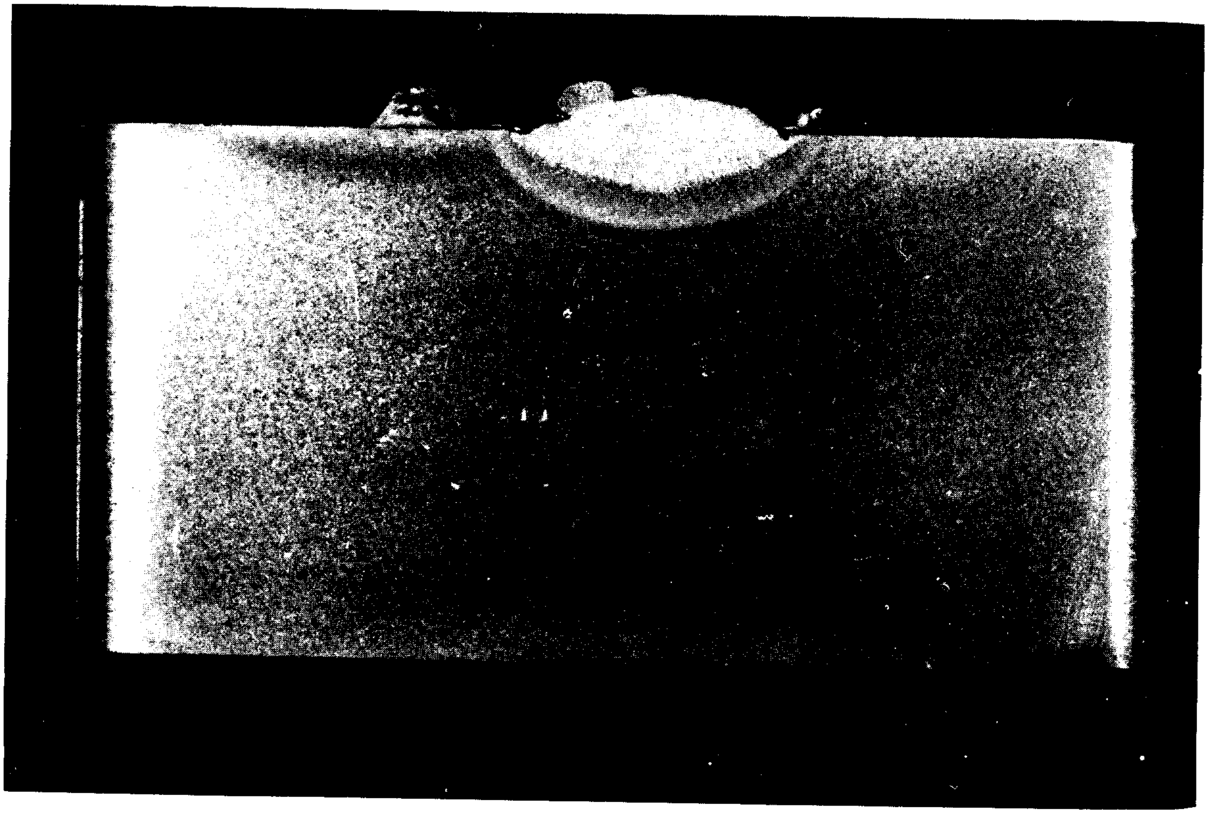


FIG. 79 - CROSS-SECTION OF WELD BEAD,
SPECIMEN 101 ($\frac{3}{4}$-INCH PLATE)

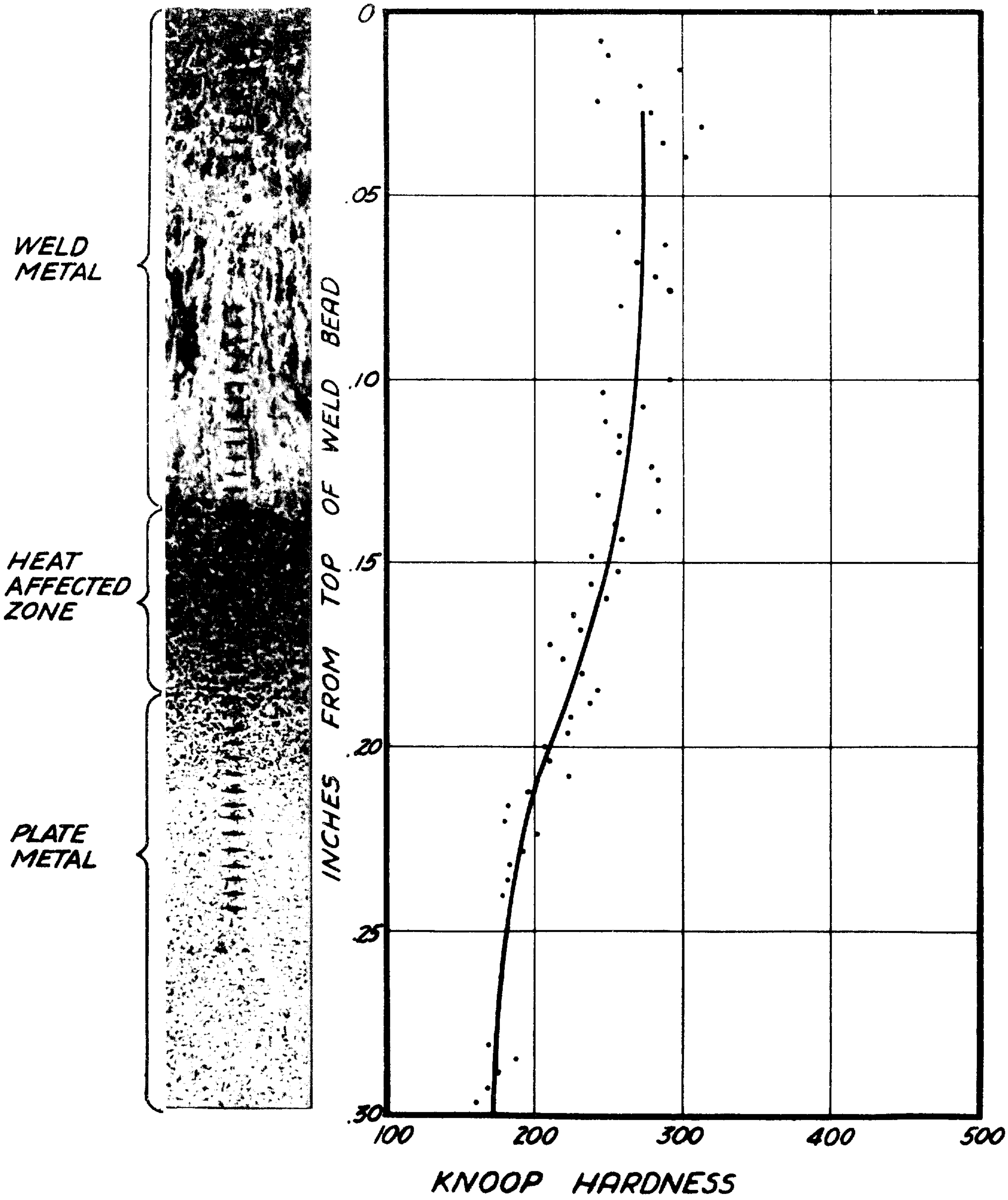


FIG. 80 - SPECIMEN 101; FLEETWELD 5 ELECTRODE; 100°F PREHEAT. (SEE TABLE 9)