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Research on the Weldability of Iron Alloys
Weldability Tests of Silicon-Manganese Steels

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ABSTRACT

An investigation on the effect of silicon content with varying carbon and manganese on mechanical properties and weldability of 24 steels indicates that silicon is to be preferred to carbon or manganese for the production of high strength normalized steels for welding; the silicon steels showed lower weld hardening and higher weld ductility results.

INTRODUCTION

AUTHORIZATION

1. This problem was authorized by Bureau of Ships multi letter L1-1(440)(275), EN 28/A2-11, of 22 June 1943, paragraph 1.

STATEMENT OF PROBLEM

2. Only a few isolated cases describing the effect of silicon on weldability are found in the literature. A number of authorities have condemned silicon steels (4)(5) for welding; others have reported no difficulty (6)(7). Spraragen and Claussen in their review of the literature on Welding Silicon Steels (8) state that "there is obvious paucity of mechanical test results on welded silicon steels. Studies could profitably be made of the effect of silicon content on welding the new low-alloy high-strength steels as well as other alloy structural steels. The effect of silicon in plain carbon steels would form the basis of these more complicated studies".

KNOWN FACTS BEARING ON THE PROBLEM

3. There has developed over the past decade a variety of low-alloy high-tensile steels both for structural and engineering uses. The advent of the war with its shortages of certain of the alloying elements has almost eliminated some of these steels and has forced changes to be made in the composition of other of the low alloy high tensile steels. The use of silicon in amounts to give alloying strength has been attractive since the available quantity of silicon is only limited by electric furnace capacity. The possibility of developing a steel with the desired mechanical properties and at the same time decreasing its hardenability to such an extent that welding is not too difficult has been the aim of many low-alloy steel designers.

4. Greiner, Marsh and Stoughton (9) in "The Alloys of Iron and Silicon" review extensive studies of constitution and mechanical properties of iron silicon alloys. No quantitative statement is made by these authors regarding the weldability of silicon steels.

5. Three surveys of tests for weldability of steels have been submitted by the Naval Research Laboratory. The first of these (1) NRL Report No. M-1642 of 15 August 1940, presented a comparison of eight types of tests for weldability. The second (2) NRL Report No. M-1770 of 20 August 1941, showed the application of these test methods to a study of the weldability of a series of 24 low-alloy nickel steels. The third (3) NRL Report No. M-1925 "Weldability Tests and Calculated Hardenability for 42 Carbon Manganese Steels" presented weldability test data and suggested a possible correlation between weldability test results and the hardenability of the

steel. In the report on the effect of carbon-manganese on the weldability of steel it was pointed out that the presence of 0.20 percent silicon was effective in reducing the manganese or carbon content permissable for straightforward welding.

6. In a discussion of the weldability of 42 carbon-manganese steels, it was pointed out (3) that hardenability* is a factor in the weldability of a steel. The use of the end quench hardenability test was suggested as a means for measuring this property. Further dependence of weldability upon the carbon content of the steel was pointed out in NRL Report No. M-1870 of April 1942.

7. During the past year the results of a series of tests (10) have been reported by Doan, Stout and Frye. This work, with certain modifications will do much to simplify the problem of weldability. In this investigation, the principle of which was originally suggested by Kinzel (14), the maximum hardness produced in a certain weld was assumed equal to that at a certain distance from the quenched end of a hardenability test bar. This distance corresponded to the particular welding conditions used in the test. Other welding techniques were represented by other distances. In order to obtain a grain size in the end-quench hardenability bar similar to that found in the heat affected zone of a weld, the test bar was heated to 2100°F at various rates and measuring the static ductility of the specimen as a slow-bend notched-bar. In this manner it is possible to obtain an indication of the welding behavior of a steel by two tests, the first for hardness and the second for ductility at that hardness.

OBJECT OF TESTS

8. This is a report of the investigation on the effect of the silicon content with varying carbon and manganese on the mechanical properties and weldability of steel. In determining the weldability of this series of steels, three factors have been considered; first, the hardness produced in the base metal by a bead weld made under a standard welding technique, second, the effect of welding on ductility as measured by the V-notched slow-bend test, and third, the relation of weldability to hardenability as measured by the end-quench hardenability test. It was also desired to analyze the data of this series in accordance with the extensive work on weldability at Lehigh University reported by Doan, Stout and Frye (10).

*Hardenability is stated in terms of "ideal critical diameter" namely the diameter of bar in inches that will just harden all the way through in an ideal quench (a quench in which the outside surface of the specimen is reduced to the temperature of the quenching medium in zero time).

COMPOSITION AND PROPERTIES OF MATERIALS USED IN THIS STUDY

9. In order to cover the desired range of carbon, manganese, and silicon, it was necessary to prepare experimental heats. Accordingly twenty seven 40 lb. ingots were made in a high frequency induction melting unit having a basic crucible. The carbon ranged from 0.18 to 0.35% with manganese varying from 0.80 to 1.50%. The silicon content was varied from 0.65 to 1.20% by adding ferro-silicon just prior to pouring each of the three ingots per heat.

10. The following melting practice was used for the above heats. A weighed amount of SAE 1015 scrap was charged in the basic crucible and melted down. The average time for melting the scrap was 37½ minutes. The heat was held for 14 minutes then 0.20% ferro-silicon (95% type) was added to quiet the heat and condition it for further additions. To adjust the carbon content, iron containing 4.25% carbon was added immediately after the first silicon addition, followed in half a minute by an addition of electrolytic manganese. Aluminum strip (1½ lbs/ton) was added 2½ minutes after the manganese for deoxidization and half a minute later the first ingot was poured into a cast iron ingot chill mold with 40 lb. capacity including hot top and pouring head. A calculated amount of ferro-silicon was next added to the remaining metal to increase the silicon content and the second split poured within a minute of the first. Another calculated amount of ferro-silicon was added to the heat to further increase the silicon content and the remaining metal poured into the third ingot mold. A pouring temperature of 2750°F, observed with an optical pyrometer, was maintained as closely as possible.

11. After the pouring heads and hot tops were removed, the twenty-seven ingots were forged to slabs 2 inches thick by 6 inches wide. They were then hot rolled to 1/2 inch thick plates. Because of the effect of variations in finishing temperatures the steels were normalized for one hour at about 100°F above the transformation range in a controlled atmosphere furnace.

12. The composition of the steels used in this study as determined by chemical analysis is given in Table I. Mechanical properties in the longitudinal direction and hardness numbers of the plate material are given in Table II. Charpy V-notched bar values at testing temperatures of 87°F and 30°F are shown in Table III.

WELDING TECHNIQUE

14. In making comparative tests it is essential to hold conditions as constant as possible; hence, full automatic welding control was used. All of the electrodes used in these tests were supplied by one manufacturer. These electrodes

were of mild steel, heavy coated, reversed ploarity (Navy Grade EA, Class 1; AWS E6010) with 3/16 inch diameter core. The plates were all thoroughly cleaned of mill and furnace scale by sand blasting before welding. N.R.L. standard welding technique for 3/16" diameter electrode with 175 amperes, 26 volts, reversed polarity and 6 inches per minute travel was used.

METHODS AND RESULTS OF TESTS

15. The following sections describe the tests as they were performed and present the data obtained from the tests on the present series of experimental silicon steels.

MAXIMUM HARDNESS AND GRAIN SIZE OF BEAD WELDS

16. Single bead-welds were deposited on plates six inches wide by seven inches long by one-half inch thick transverse to the direction of rolling by using automatic welding with 175 amperes, 26 volts and a speed of travel of 6 inches per minute. Vickers (10 kg) hardness surveys were made on polished transverse sections of the bead welds. Plate 1 shows the type of survey used for the test specimens. Test values for maximum hardness are reported in Table IV. A record was kept of the location of the indent with highest hardness. A survey of the grain size at the fusion line was made on the steels by photographing the structure of the heat affected zone at 150 magnification and actually counting the enlarged grains for three locations to a depth of 0.02 inch below the fusion line on the bead weld section. Typical photographs of the microstructure at the fusion line are shown in Plate 2 with the areas outlined which were used in determining the grain size. Test values for maximum hardness and fusion line grain sizes are reported in Table IV.

V-NOTCHED SLOW-BEND TESTS

17. Strips 1½ inch wide were cut (Plate 3) transverse to the direction of the bead weld from the test weldments described above. Only sufficient metal was removed from the top surface to eliminate irregularities. Material was then removed from the lower surface to obtain a specimen 0.375 inch thick. The specimens were etched in a 5% nital solution and the location of the V-notch was determined by scribing a line on the side of the specimen parallel to and at a distance of 0.315 inch from the bottom of the specimen (Plate 4). The V-notch was located at the point of intersection of this line with the line of fusion between the weld metal and plate material. In this manner the apex of the standard V-notch was machined tangent to the fusion line. For comparison a similar specimen prepared from the unaffected plate material was tested (Plate 5). The specimens were bent to failure in a guided-bend test jig. The angle at maximum load for each specimen was noted and stress-strain diagrams were obtained. Data for the V-notch slow-bend test are presented in Table V.

END-QUENCH HARDENABILITY TEST

18. Since most of the material used in this study was available only in 1/2 inch thickness, $1\frac{1}{2}$ inch rounds for the end-quench hardenability test were forged from the plate material. The pieces were normalized for $2\frac{1}{2}$ hours at 100°F above the transformation range before machining. End quench hardenability test bars (Plate 6a) were machined from these forged bars. These specimens were inserted into a carbon jacket and maintained at 2100°F in a controlled atmosphere Globar furnace for 30 minutes and then quenched in a standard (11) jig (Plates 7 and 8). The specimens were allowed to remain in the quenching jig for ten minutes or until cold. Two flat surfaces were ground along the full length of the specimens (Plate 6b) at points 180° apart to a depth of from 0.025 to 0.040 inch. The flat surfaces were prepared by hand polishing through #000 emery paper and the Vickers method with 10 kg. load was used for the hardness study. The first indent was made at 0.015 inch from the quenched end; the next 14 indents were spaced at 0.025 inch and at least 14 additional indents were made with a spacing of 0.050 inch. A number of the end-quenched specimens showed a hardness at the quenched end far below that predicted for maximum hardness for the carbon content. No decarburization was revealed by microscopic examination. In order to determine whether the low hardness was caused by retained austenite all the end quench test bars were cooled in a bath of liquid air. These specimens were again ground and indented for the Vickers hardness survey. The increase in the hardness at and near the quenched end of the bar was readily noted.

19. The grain size of the end-quench hardenability test bars was determined by polishing the specimen electrolytically, etching with nital-picral reagent and photographing a suitable microstructure along the bar at 100 x magnification. An actual grain count was made for an area on the photograph of 5,000 square millimeters. The chemical analyses for carbon, manganese and silicon in the steels used in this portion of the study were made on samples drilled from the end quench bar. The chemical analysis for the residual elements of each heat was on the original stock.

20. The distance along the bar which was taken for determination of "ideal diameter" for full hardening was based on the hardness level indicated by the line for 50 percent martensite (Plate 9) for plain carbon steel. This distance was converted to ideal diameter by the relation given in Plate 10. These curves have been presented by Grossmann (12) and have been reproduced here with the Rockwell hardness values converted to the Vickers scale (13).

21. The "ideal diameter" of each steel was corrected to a grain size of 2 by use of the chart in Plate 11. The empirical relation of $(D_i)^2/D_i$ which is the ratio of the square of the hardenability of the steel (corrected to a grain size No. 2) to the hardenability for the pure iron-carbon portion of the steel is used in the analysis of the data. The analysis of the data from this standpoint is given in Table VI. Since this relation is empirical no further statement as to its metallurgical significance is made at this time.

22. The hardenability of the steels used in this study was also calculated using the methods* proposed by Grossmann (12) using the Factors shown in Plates 12 and 13. The observed hardenability of silicon for the steels in this study when quenched from 2100°F is not so great as that predicted by Crafts and Lamont (16) or Grossmann (12)

CONTINUOUS COOLED U-NOTCH SLOW-BEND (LEHIGH)

23. Specimens 6 inches long by 1 inch wide by 0.25 inch thick were prepared. These specimens were heated to 2100°F in an controlled atmosphere Globar furnace and maintained at temperature for 30 minutes. The specimens were bent to

* In the method proposed by Grossmann, a steel is considered as having a base hardenability due to its carbon alone and this base hardenability is multiplied by a factor for each chemical element present. After multiplying all these together, the final product is the hardenability. Grain size may be taken into account either on the base hardenability or after multiplication. The factors for carbon content of a steel with a given austenitic grain size may be obtained from Plate 12. Factors for the other constituents may be obtained from Plate 13.

The following composition for steel #226 may be used as an illustration of the method of calculation (austenitic grain size 2.3).

Composition	Percent	Factor
C	0.18	0.206
Mn	0.86	3.85
Si	1.12	1.62
S	0.038	0.98
P	0.015	1.04
Al	0.04	1.13
Cu	0.23	1.08
Ni	0.14	1.05
Cr	0.05	1.10
Mo	0.02	1.06

Product of Factors D_i = 1.96 in.

failure in a guided bend testing jig with the specimens placed in the jig with the notch facing the opening in the female member of the jig. The angle at maximum load on each specimen was noted. Stress-strain diagrams were also obtained. Vickers hardness measurements were made on a section taken from each test specimen at a distance below the surface equal to the depth of the notch. Table VII presents data obtained from these tests. More will be said in the discussion regarding the low hardness obtained for many of the brine quenched specimens.

24. We are continually confronted with the problem of conversion of the results for one type of test piece in terms of another type. The relation of the angles at maximum load for the U-notch and V-notch slow bend specimens is shown in Plate 15. A comparison may be made between the specimens with the steel in the normalized condition, or the results of V-notched bead weld specimens may be compared with U-notch slow bend specimens continuously cooled to a hardness equal to the maximum hardness measured on the bead weld. These results indicate that an angle of bend of 35 degrees for the U-notched specimen is approximately equivalent to an angle of bend of 20 degrees for the V-notched specimen.

DISCUSSION OF RESULTS

25. The results of tests for the present series of steels together with other data presented by Walters (17) permits the construction of Plate 16 showing the relative effect of silicon and manganese on the tensile strength in the normalized condition. The accuracy of the method of calculating the tensile strength of normalized steels from chemical composition suggested by Walters (17) can be seen by comparison with the actual tensile strengths of the steels used in the present study (Table VIII). It is to be seen (Plate 17) that in a silicon-manganese steel, manganese is only slightly more effective than silicon in increasing the tensile strength of normalized steel.

26. Increasing the silicon content of any of the steels in this study in the range 0.60 to 1.20 percent affects the weldability as measured by maximum bead weld hardness and ductility only moderately. The results of these tests indicate that less weld hardening and better weld ductility is to be obtained by the use of silicon in preference to manganese. The reported difficulties due to high ingot shrinkage and rolling difficulties which are encountered in steel mill practice may upset this advantage. Also for a given tensile strength better ductility and notched-bar impact results are to be obtained in the manganese steels. The practical solution for a high-tensile low-alloy steel may well be a compromise between the improved weldability due to silicon and the improved mechanical properties due to manganese.

DISCUSSION OF END-QUENCH HARDENABILITY RESULTS

27. It has been suggested by Kinzel (14) that each combination of welding conditions corresponds to a position on the end-quench hardenability bar. From the data presented by Doan and Stoud (10) a welding technique of 175 amperes, 26 volts and 6 inches per minute corresponds to a distance of 0.34" from the quenched end. The maximum bead weld hardness for a number of steels is compared with the end quench test bar hardness at 0.34" distance in Plate 18. Further data for the steels used in this study are presented in Plate 19. The trend of the correlation is in general accurate only to plus or minus 20 percent. It will be realized that this is not entirely satisfactory for the welding engineer except as a preliminary indication since this might predict a hardness of 240 to 360 for a steel whose actual maximum hardness is 300. Thus it is necessary to analyze the end quench hardenability test data further in order to determine the other factors which control the hardness at any given distance along the bar.

28. The maximum hardness that may be obtained by drastic quenching is dependent upon the carbon content alone (Plate 9). The hardness attained by less drastic methods of cooling will be determined by the carbon content as well as the alloy content. It has been pointed out (15) that the hardness attained by any steel under a given welding technique is affected by the carbon content as well as the hardenability of the steel. The most convenient method of analysis is that shown in Plate 20, where a relation is shown between $D_i'^2/D_i''$* and the percent of maximum quench hardness attained at 0.34" distance along the bar. Further analysis of the end-quench hardenability test results indicate a definite correlation at a distance greater than 0.2" along the bar for the steels used in this study. This agreement is not as good for shorter distances, especially for the higher hardenability steels. This is to be expected as small variations in the temperature of the quenching water, or in the exact technique used in handling the specimen will influence the results at the quenched end. The hardness attained at the shorter distances will also be influenced by any retained austenite present in the rapidly quenched portion of the test piece. This effect can be partially overcome by a low temperature treatment of the end quench hardenability test bar with dry ice or liquid air before measuring the hardness. The above analysis also can be applied to the correlation of weld hardening with end quench hardenability test results. The scatter of the data may be reduced by correcting for grain size both in the end-quenched bar (Plate 11) and in the heat affected zone (Plate 12) of the bead weld; such an analysis is shown in Plate 21.

* D_i' = ideal diameter corrected to grain size No. 2

D_i'' = ideal diameter for iron-carbon only.

29. The use of hardenability calculated from chemical composition gives results that show somewhat greater scatter than obtained by actual measurement using the end-quench hardenability bar.

30. There has been a constant attempt to simplify the metallurgy of welding even to an extent beyond that possible in ordinary heat treatment practice. The metallurgy of welding even in its simplest case, that of a bead weld on a plate, is complicated by high temperatures, grain growth and drastic changes in the thermal cycle, together with conditions of diffusion and stress. In general equilibrium conditions are rare.

31. The present study indicates that in addition to the end-quench hardenability test data, it is necessary for a full analysis to have the carbon content and the grain sizes for the end-quench bar and the heat affected zone. Very few data are available at this time for the effect of welding technique on grain growth in the heat affected zone. We have evidence that higher energy input in the welding cycle in some steels may increase the grain size sufficiently to affect the hardenability so that a greater maximum hardness results with increased welding currents. Further simplification of such data by use of charts or other means is highly desirable and will be possible when a more complete analysis of the metallurgy of welding is available.

DISCUSSION OF CONTINUOUS COOLED U-NOTCH SLOW-BEND RESULTS

32. The use of brine and oil quench and air and furnace cool does not always give sufficient variation in hardnesses to establish the relation of hardness and ductility. There is need for a specimen with an intermediate cooling rate between the oil quench and air cool. Several methods have been tried but so far no procedure has proven entirely satisfactory or reproducible.

33. One of the most surprising observations in this investigation was the low hardness accompanied by low ductility found in many of the brine quenched specimens. For example, in steel #226 the oil quenched specimen had a hardness of 309 while the brine quenched specimen had a hardness of only 188. The angles at maximum load, however, were 16 and 14 degrees respectively. This indicated that the brine quenched specimen probably contained considerable retained austenite which was rapidly transformed during test by the high tensile stress at the apex of the notch. In order to determine if this were the case, sections of the brine quenched specimens were treated in a liquid air (-185°C) bath and the hardness measured (Table VII). In all cases the hardness increased and in most cases became greater than that of the oil quenched specimen. Steel #226 increased in Vickers hardness from 188 to 413. This indicates the presence of a surprising amount of retained austenite in this steel. Many of the other steels likewise show the presence of retained austenite.

SUMMARY AND CONCLUSIONS

34. From the results of this study a number of conclusions are indicated:

1. Silicon is almost as effective as manganese in increasing the tensile strength in the normalized condition.

2. The use of silicon as a strengthener of normalized steels for welding is to be preferred to that of carbon or manganese as lower weld hardening and higher weld ductility results in the silicon steels.

3. The presence of retained austenite has been observed with a carbon content as low as 0.18% with 0.86% manganese and 1.12% silicon in specimens quenched drastically from 2100°F. This observation must be kept in mind in the use of these steels for welded structures as tensile stresses in service will have the tendency to transform the austenite giving a dangerous, high hardness product with low ductility.

4. Weld hardening results are dependent upon the carbon content and hardenability of a steel and both must be considered in analyzing the effect of a welding technique on hardness.

35. In future work the weldability of silicon-manganese steels with silicon contents up to 0.60% should be studied. Further dilatometric work on silicon steels would be useful. The effect of grain size in the heat affected zone on weld hardening should be further investigated. Finally the effects of variations in welding technique and thickness of plate should be continued. The field of metallurgy of welding is still intensely complicated by a large number of variables. The field of metallurgy of welding has taken great strides in the recent years and possibly the day is not too far away when studies of welding will help in untangling some of the mysteries of metallurgical behavior.

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TABLE I CHEMICAL COMPOSITION OF STEELS USED IN THIS STUDY

Steel No.	C	Mn	Si	S	P	Cu	Ni	Cr	Mo	Al
224	0.18	0.84	0.66	0.038	0.016	0.23	0.14	0.05	0.02	0.03
227	0.19	1.04	0.67	0.039	0.014	0.23	0.12	0.05	0.02	0.03
230	0.22	1.44	0.69	0.037	0.013	0.20	0.09	0.06	0.02	0.03
233	0.25	0.86	0.69	0.039	0.014	0.22	0.10	0.05	0.02	0.03
239	0.29	1.40	0.70	0.040	0.013	0.23	0.10	0.05	0.02	0.03
236	0.28	0.92	0.71	0.040	0.013	0.22	0.10	0.05	0.02	0.03
247	0.35	1.06	0.72	0.040	0.013	0.22	0.10	0.05	0.02	0.03
242	0.35	0.85	0.73	0.037	0.013	0.22	0.10	0.06	0.02	0.03
228	0.22	1.04	0.87	0.038	0.014	0.23	0.12	0.05	0.02	0.03
231	0.22	1.48	0.90	0.039	0.013	0.20	0.09	0.06	0.02	0.03
234	0.24	0.86	0.90	0.038	0.013	0.22	0.10	0.05	0.02	0.03
240	0.29	1.40	0.92	0.041	0.013	0.22	0.10	0.05	0.02	0.03
225	0.19	0.84	0.93	0.039	0.014	0.23	0.14	0.05	0.02	0.03
243	0.33	0.86	0.94	0.038	0.013	0.22	0.10	0.05	0.02	0.03
245	0.35	1.07	0.94	0.040	0.012	0.23	0.10	0.05	0.02	0.03
249	0.32	1.49	0.94	0.039	0.012	0.22	0.10	0.06	0.02	0.03
226	0.18	0.86	1.12	0.038	0.015	0.23	0.14	0.05	0.02	0.04
232	0.20	1.50	1.12	0.039	0.014	0.20	0.10	0.06	0.02	0.03
235	0.24	0.88	1.12	0.038	0.012	0.22	0.10	0.05	0.02	0.03
229	0.20	1.07	1.14	0.037	0.012	0.23	0.12	0.05	0.02	0.03
241	0.28	1.40	1.15	0.038	0.013	0.23	0.10	0.05	0.02	0.03
246	0.35	1.07	1.17	0.040	0.013	0.22	0.10	0.05	0.02	0.03
238	0.26	0.93	1.18	0.040	0.012	0.23	0.10	0.05	0.02	0.03
250	0.31	1.50	1.19	0.039	0.012	0.22	0.10	0.05	0.02	0.03

TABLE II MECHANICAL PROPERTIES OF STEELS USED IN THIS STUDY

Steel No.	Yield Strength* psi	Tensile Strength psi	Elongation Percent	Reduction of Area Percent	Hardness Vickers
224	54,350	78,200	37.5	66.0	154
227	58,500	81,800	37.1	64.4	164
230	69,050	91,000	36.4	70.0	182
233	59,600	84,500	36.1	63.9	166
239	68,750	95,950	33.2	65.4	197
236	59,600	87,300	35.0	63.3	175
247	63,900	98,950	32.5	59.7	192
242	63,200	95,300	32.5	57.0	188
228	51,500	83,300	36.1	65.7	172
231	64,500	96,650	34.3	68.4	192
234	60,850	87,350	35.0	65.2	176
240	73,100	101,500	32.5	65.6	201
225	51,350	78,900	36.8	64.7	162
243	67,500	96,400	32.8	58.7	193
245	69,800	100,800	32.2	60.4	200
249	79,900	107,600	31.1	64.2	210
226	64,500	83,800	36.6	67.6	169
232	53,700	95,400	33.2	65.2	196
235	66,150	90,300	33.9	64.5	182
229	53,900	86,700	35.7	65.6	178
241	60,000	100,750	32.6	64.4	207
246	71,450	103,900	30.7	60.9	202
238	51,850	90,700	34.3	62.4	182
250	83,500	110,400	31.1	62.2	220

* Test specimen taken in longitudinal direction.
Diameter of specimen 0.357". Gage length 1.4".

TABLE III RESULTS OF CHARPY V-NOTCHED BAR (IMPACT) TEST

Steel No.	Testing Temperatures 87°F ft/lb.	30°F ft/lb.
224	77	68
227	83	48
230	70	72
233	69	44
239	64	37
236	69	40
247	42	29
242	41	26
228	42	34
231	57	39
234	69	42
240	54	36
225	70	56
243	34	19
245	35	27
249	56	36
226	74	32
232	64	10
235	56	34
229	36	17
241	43	28
246	37	23
238	26	20
250	50	29

TABLE IV MAXIMUM BEAD WELD HARDNESS AND GRAIN SIZE OF HEAT AFFECTED ZONE

Steel No.	Bead Weld Hard-ness‡	Maximum Quench Hardness	% of Max. Quench Hardness	Grain Size Heat Affected Zone 1	2	3
224	233	495	47	3.5	3.7	3.3*
227	237	505	47	3.8	4.0	3.9*
230	306	540	57	3.3*	3.8	2.7
233	251	575	44	3.3*	---	3.0*
239	376	620	58	3.2*	3.7	3.7
236	281	606	46	2.8	2.8*	3.3
247	368	675	54	2.9	4.3	3.3*
242	330	675	49	3.7	4.2*	3.7
228	268	540	49	3.2*	---	2.7
231	306	540	57	3.2	3.4	3.1*
234	260	565	46	3.3*	4.4	3.2
240	389	620	63	2.6	3.4*	3.3
225	234	505	46	2.8	3.6*	2.3
243	333	655	51	3.2	3.9*	3.5
245	405	675	60	3.3	4.0*	4.0
249	437	645	68	2.7*	---	3.1
226	236	495	48	2.6	3.0*	2.6
232	317	520	61	3.6*	3.7	3.6
235	274	565	48	3.3	4.3*	3.4
229	264	520	51	3.3*	4.5	3.2
241	388	606	64	2.3	2.9	3.3*
246	373	675	55	3.0	3.8*	3.3*
238	265	585	45	3.4*	3.6	2.9
250	437	640	68	2.7*	---	2.9

* Zone of maximum Vickers Hardness

‡ Vickers (10 kg.)

TABLE V SLOW BEND (V-NOTCHED) TEST RESULTS (175 amp.)

Steel No.	Plate		Bead Weld	
	Angle Degrees	Maximum Load-lbs.	Angle Degrees	Maximum Load-lbs.
224	32	4680	23	4810
227	33	4920	24	5070
230	28	5345	11	4860
233	29	4845	18	2780
239	25	5435	10	5010
236	26	4920	13	4790
247	21	5200	7	4625
242	20	5050	9	4615
228	32	5150	21	5120
231	26	5635	13	5220
234	25	4990	19	5055
240	22	5495	7	4775
225	31	4850	25	5035
243	20	5200	15	5030
245	21	5410	6	4495
249	19	5740	4	4190
226	30	5035	24	5140
232	28	5750	12	5185
235	25	5145	16	5075
229	29	5260	21	5265
241	21	5560	7	4910
246	20	5420	6	4645
238	27	5380	17	5120
250	18	5840	3	4340

TABLE VI ANALYSIS OF END QUENCH HARDENABILITY TEST DATA (2100°F Quenching Temperature)

Steel No.	%C	Average Grain Size	D_i*	D_i'	D_i''	$\frac{(D_i')^2}{D_i''}$
224	0.18	2.0	1.80	1.80	0.21	15.4
227	0.19	1.2	1.85	1.70	0.22	13.1
230	0.22	1.6	2.70	2.60	0.24	28.1
233	0.25	1.7	1.95	1.90	0.24	15.0
239	0.29	2.2	2.20	2.25	0.27	18.8
236	0.28	1.6	2.00	1.95	0.27	14.1
247	0.35	1.6	2.50	2.40	0.30	19.2
242	0.35	1.9	2.10	2.07	0.30	14.3
228	0.22	1.6	1.95	1.90	0.24	15.0
231	0.22	1.9	2.55	2.50	0.24	26.0
234	0.24	1.7	2.00	1.95	0.24	15.8
240	0.29	2.3	2.50	2.60	0.27	25.0
225	0.19	1.4	1.75	1.67	0.22	12.7
243	0.33	1.8	2.05	2.00	0.29	13.8
245	0.35	2.4	2.35	2.45	0.30	20.0
249	0.32	2.2	3.05	3.10	0.29	33.2
226	0.18	2.3	1.75	1.80	0.21	15.4
232	0.20	1.9	2.50	2.48	0.23	26.7
235	0.24	1.7	1.80	1.75	0.24	12.7
229	0.20	2.4	1.90	1.95	0.23	16.5
241	0.28	1.8	2.75	2.70	0.26	28.1
246	0.35	1.5	2.30	2.20	0.36	16.1
238	0.26	1.6	2.00	1.95	0.26	14.6
250	0.31	2.8	2.95	3.20	0.28	36.6

D_i = "ideal diameter" from Test Bar

D_i' = D_i corrected to Grain Size No. 2.0

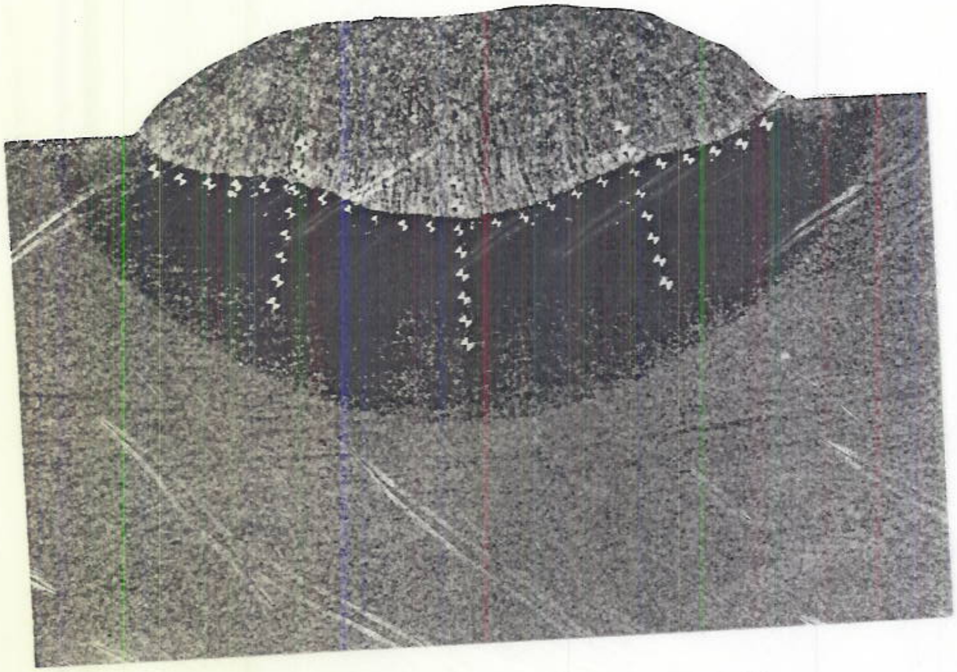
D_i'' = "ideal diameter" for Iron-Carbon only

TABLE VII RESULTS FOR CONTINUOUS COOL U-NOTCH SLOW BEND (2100°F)

Steel No.	Angle at Maximum Load				Average Vickers Hardness Number				
	Brine	Oil	Air	Furnace	Brine followed by liquid air	Brine	Oil	Air	Furnace
224	5	13	65	94	435	390	306	185	151
227	15	13	64	65	450	380	319	194	158
230	10	13	45	68	464	415	455	213	172
233	5	8	49	67	483	409	457	194	163
239	5	11	34	39	519	508	399	227	188
236	9	9	49	55	500	285	480	209	170
247	10	9	37	43	592	413	548	228	187
242	10	10	37	41	566	397	554	226	182
228	15	15	57	54	452	361	349	199	183
231	15	15	43	61	475	366	314	224	180
234	8	10	50	63	493	322	457	207	165
240	11	12	37	51	536	294	498	231	189
225	12	15	61	76	429	411	304	193	160
243	8	7	38	34	566	440	542	224	186
245	7	10	38	32	575	345	355	235	194
249	10	11	32	38	575	480	403	248	206
226	14	16	62	92	413	188	309	209	160
232	15	16	41	60	470	339	425	229	166
235	11	11	49	51	473	296	459	207	171
229	15	15	52	61	452	423	317	212	170
241	16	14	26	47	533	313	401	245	196
246	11	10	37	40	566	572	548	239	197
238	9	13	47	53	486	475	378	209	177
250	13	15	29	44	572	514	381	256	206

TABLE VIII COMPARISON OF ACTUAL AND CALCULATED TENSILE STRENGTH

Steel No.	Tensile Strength psi	
	Actual	Calculated
224	78,200	77,000
227	81,800	80,500
230	91,000	89,700
233	84,500	84,600
239	95,950	98,500
236	87,300	89,300
247	98,950	98,000
242	95,300	94,200
228	83,300	83,700
231	96,650	94,000
234	87,350	86,700
240	101,500	101,800
225	78,900	81,600
243	96,400	96,400
245	100,800	101,500
249	107,600	106,200
226	83,800	83,200
232	95,400	94,800
235	90,300	90,000
229	86,700	88,400
241	100,750	104,000
246	103,900	104,300
238	90,700	92,800
250	110,400	110,000

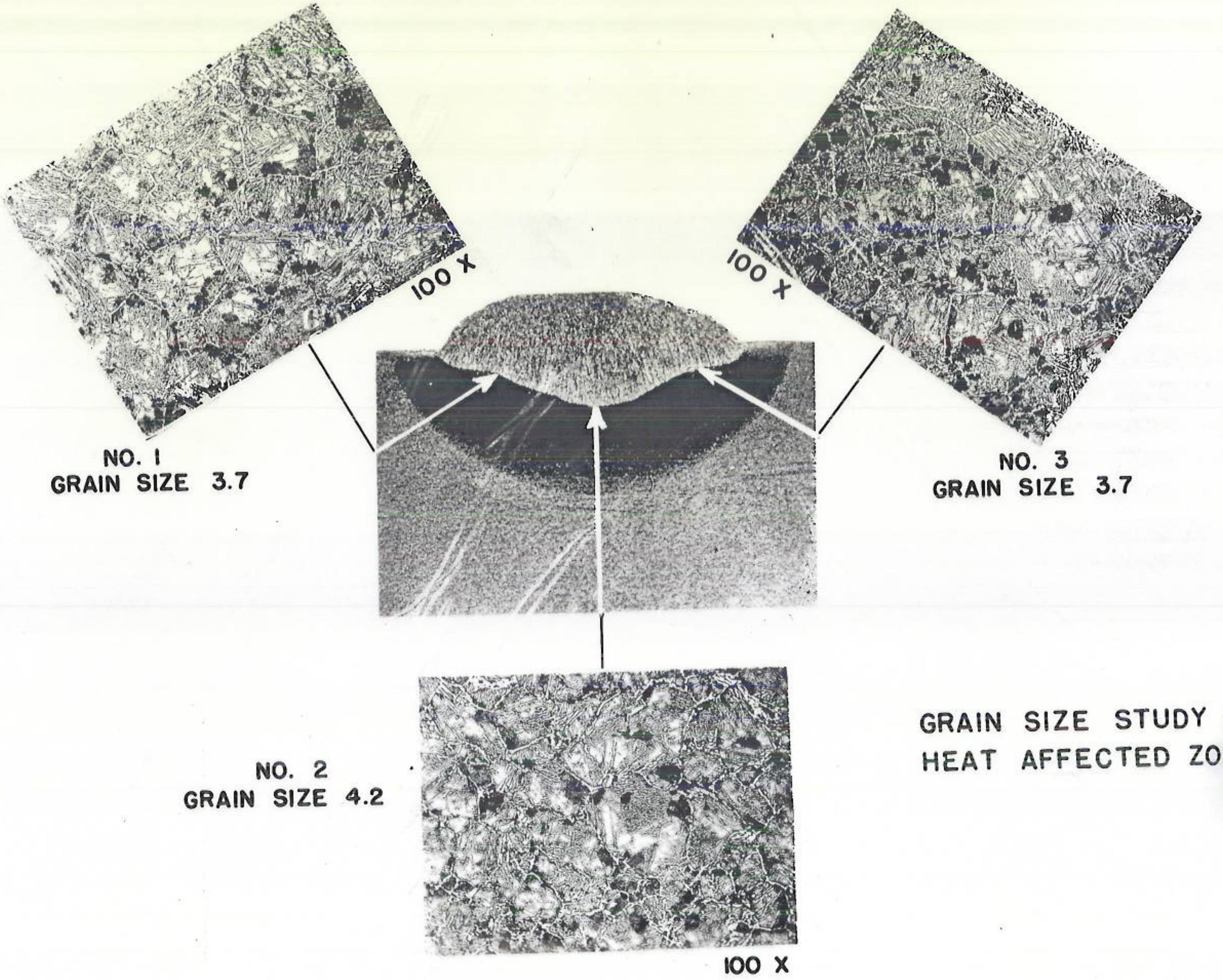


SECTION OF BEAD WELD
SHOWING HARDNESS SURVEY.

PLATE I

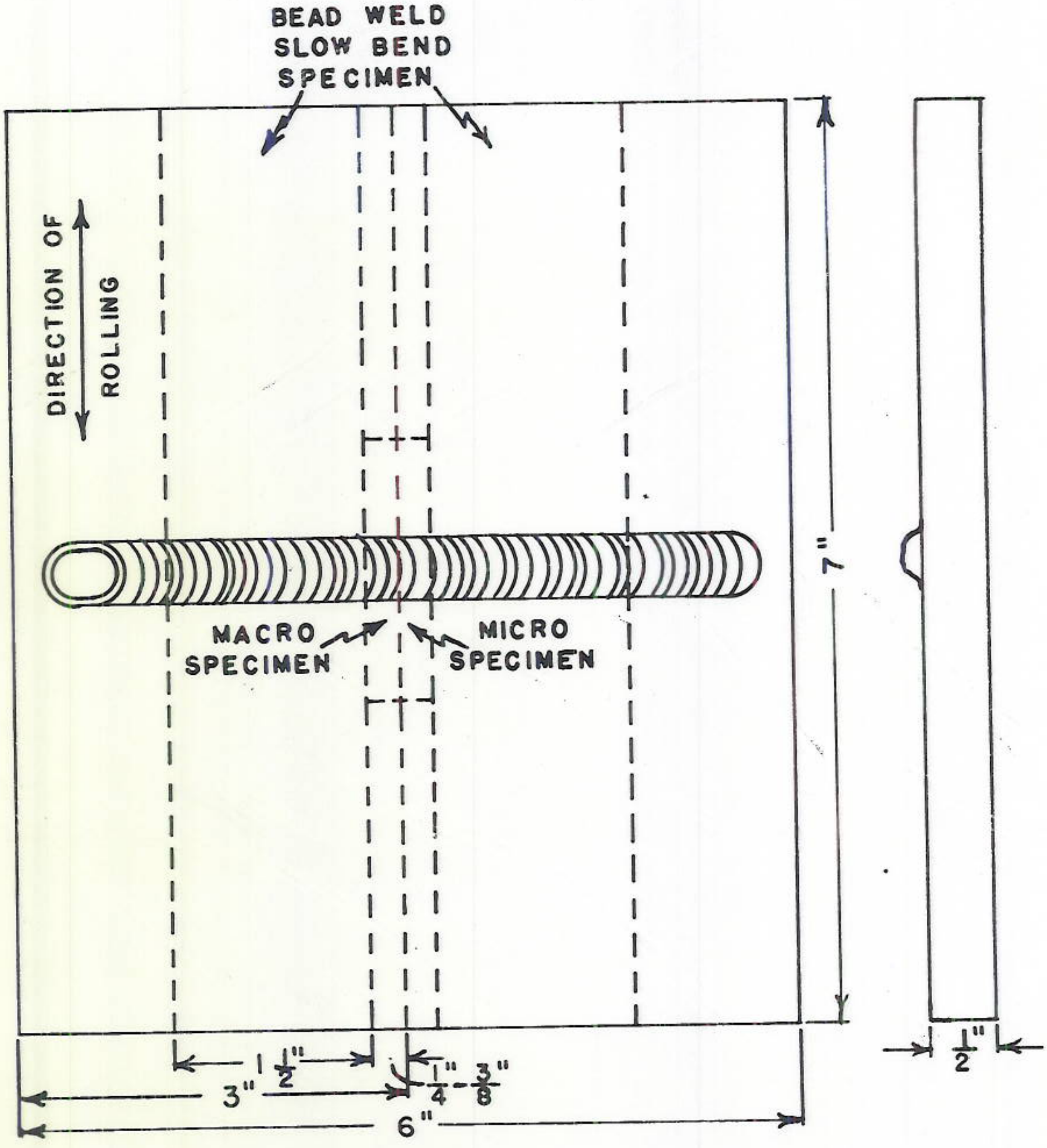
21 plates 2149

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21



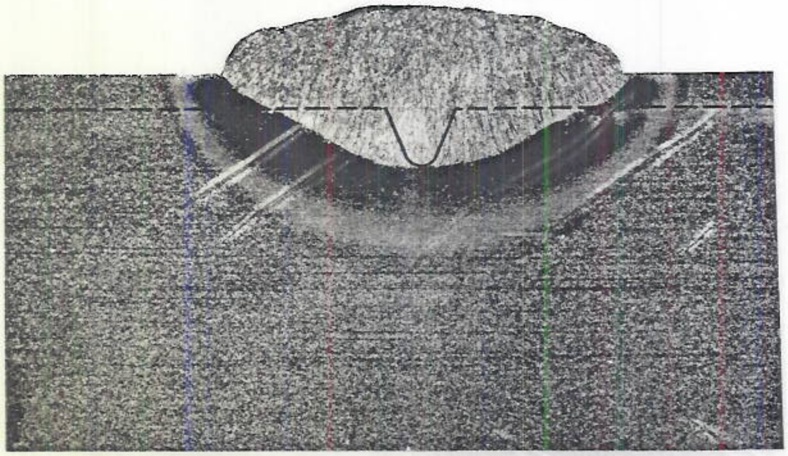
GRAIN SIZE STUDY OF
HEAT AFFECTED ZONE.

PLATE 2

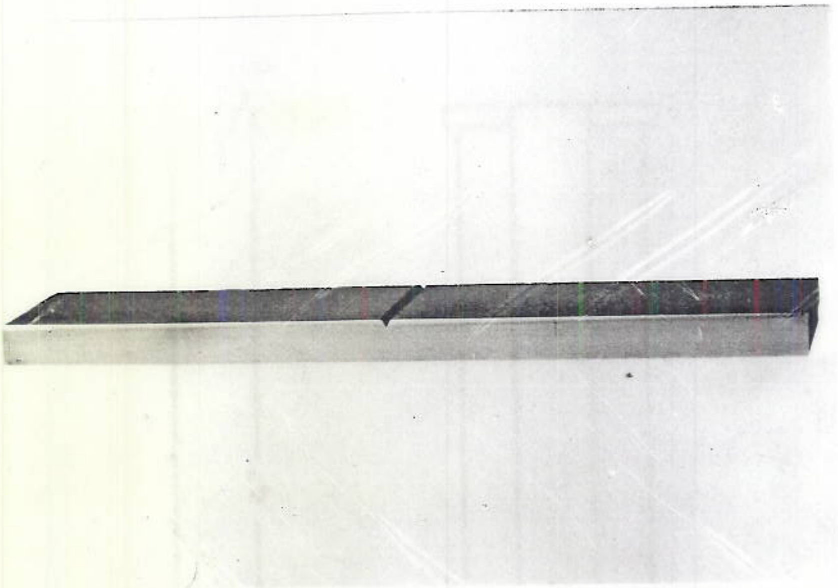


DETAILS OF BEAD WELD TEST SPECIMEN

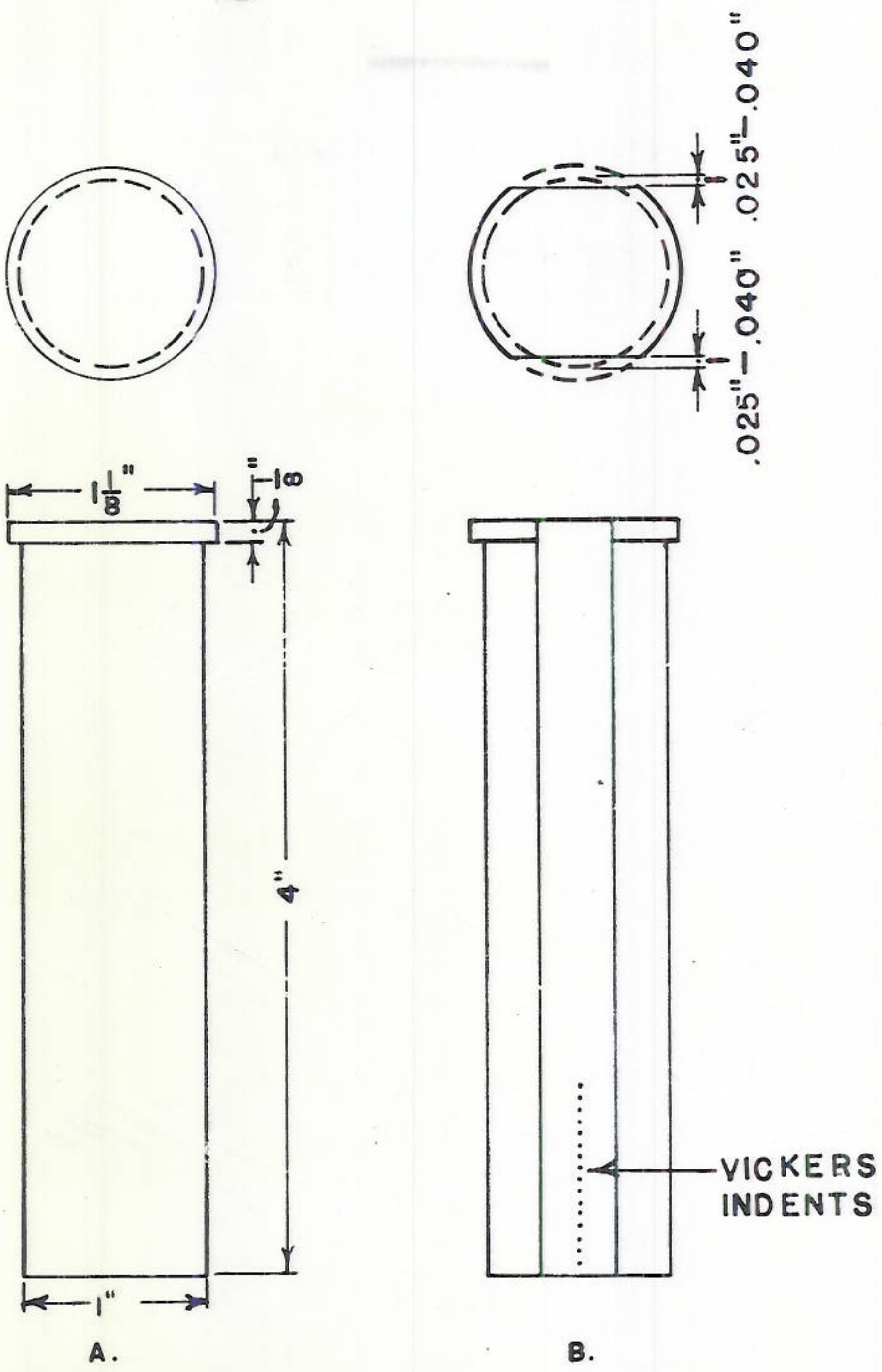
PLATE 3



BEAD WELD. SHOWING LOCATION OF V-NOTCH.
(MAGNIFICATION 4X)

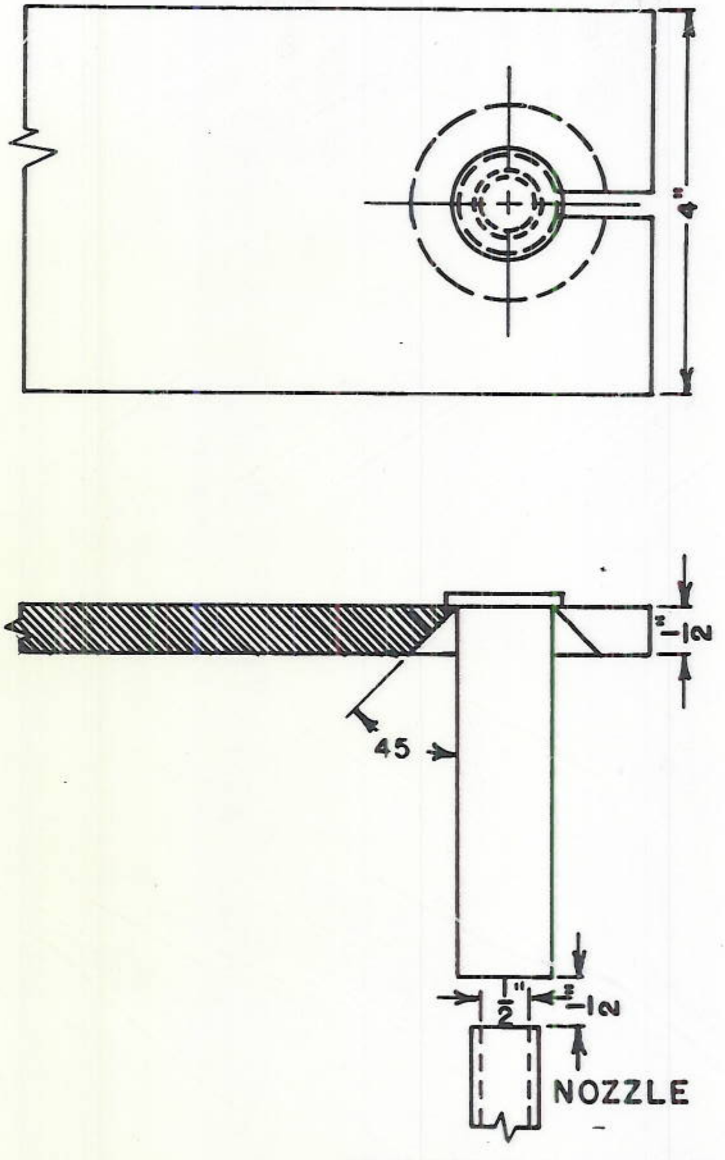


V- NOTCHED SLOW-BEND SPECIMEN



DETAILS OF END QUENCH HARDENABILITY TEST BAR

PLATE 6

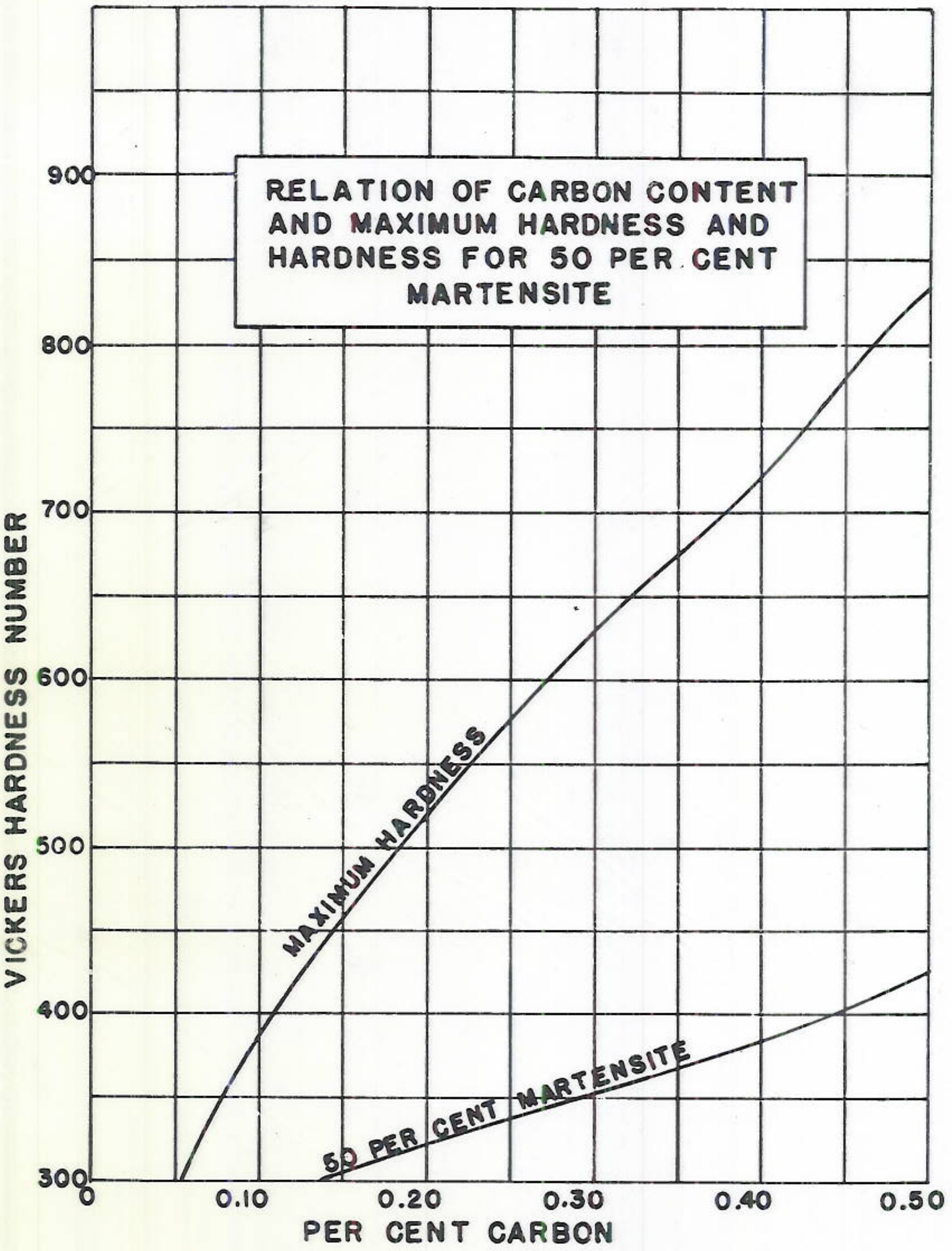


QUENCHING JIG WITH BAR IN POSITION

PLATE 7

QUENCHING EQUIPMENT WITH BAR IN POSITION

PLATE 8



RELATION OF CARBON CONTENT AND MAXIMUM HARDNESS AND HARDNESS FOR 50 PER CENT MARTENSITE

PLATE ·9

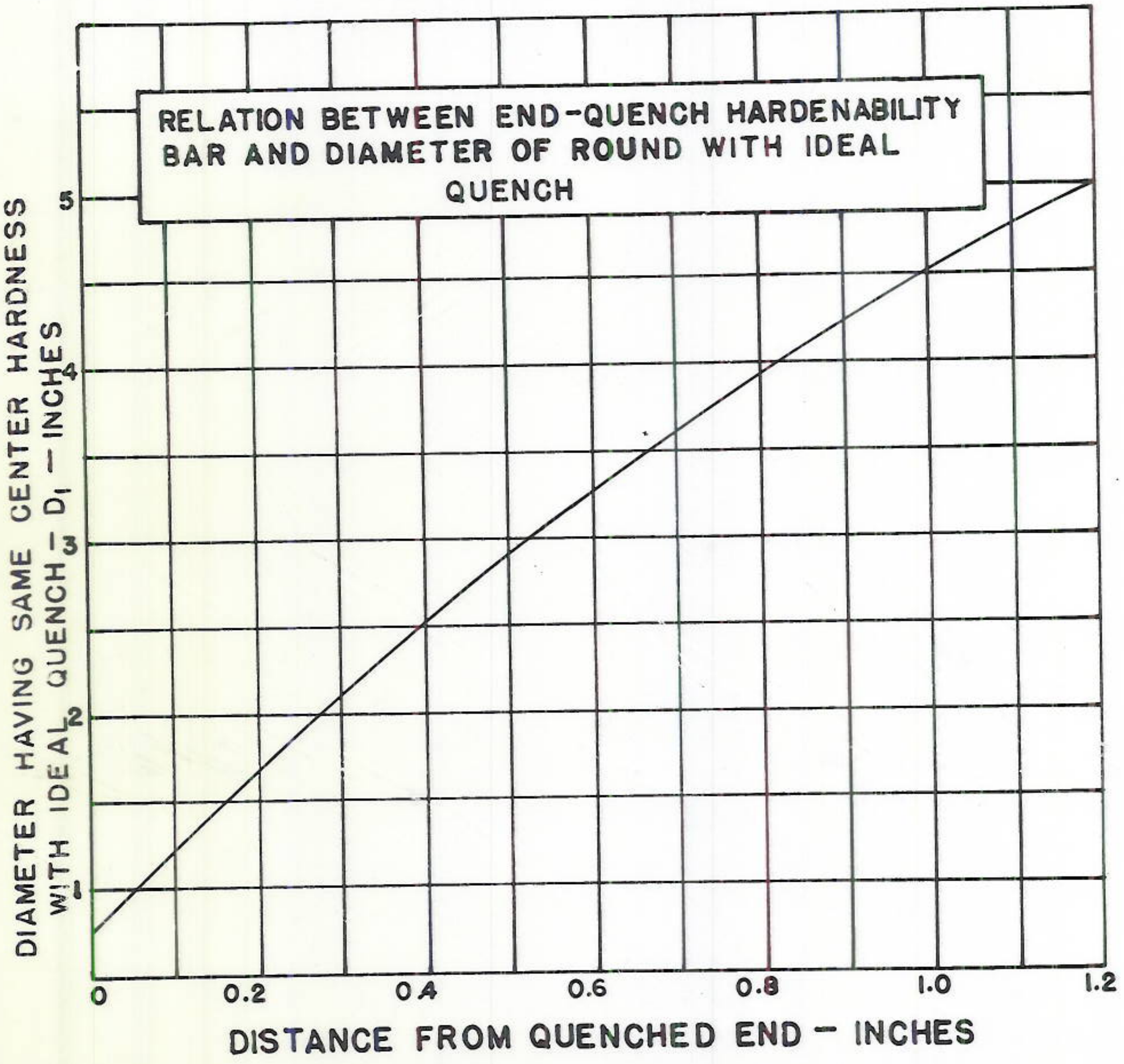
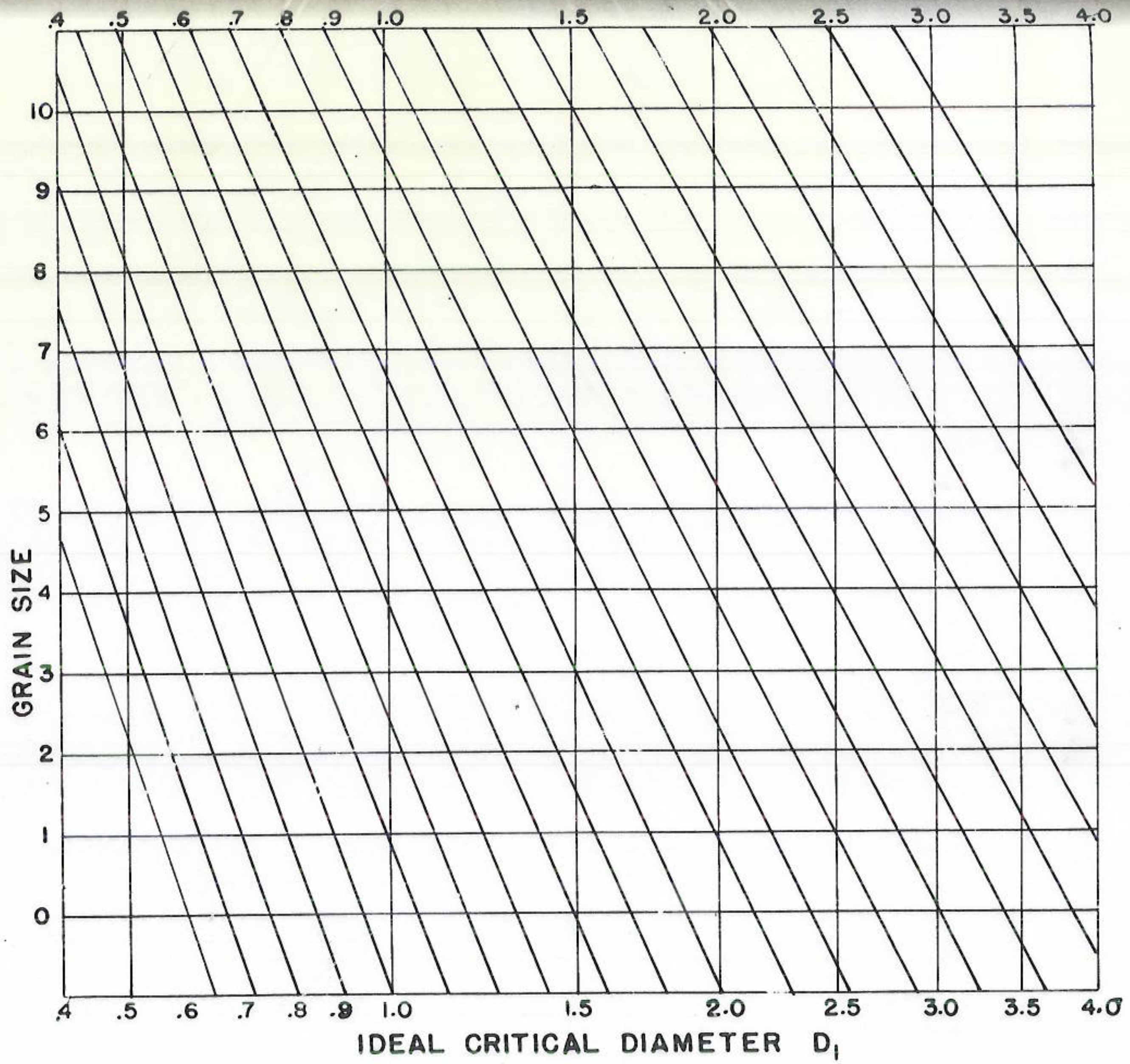
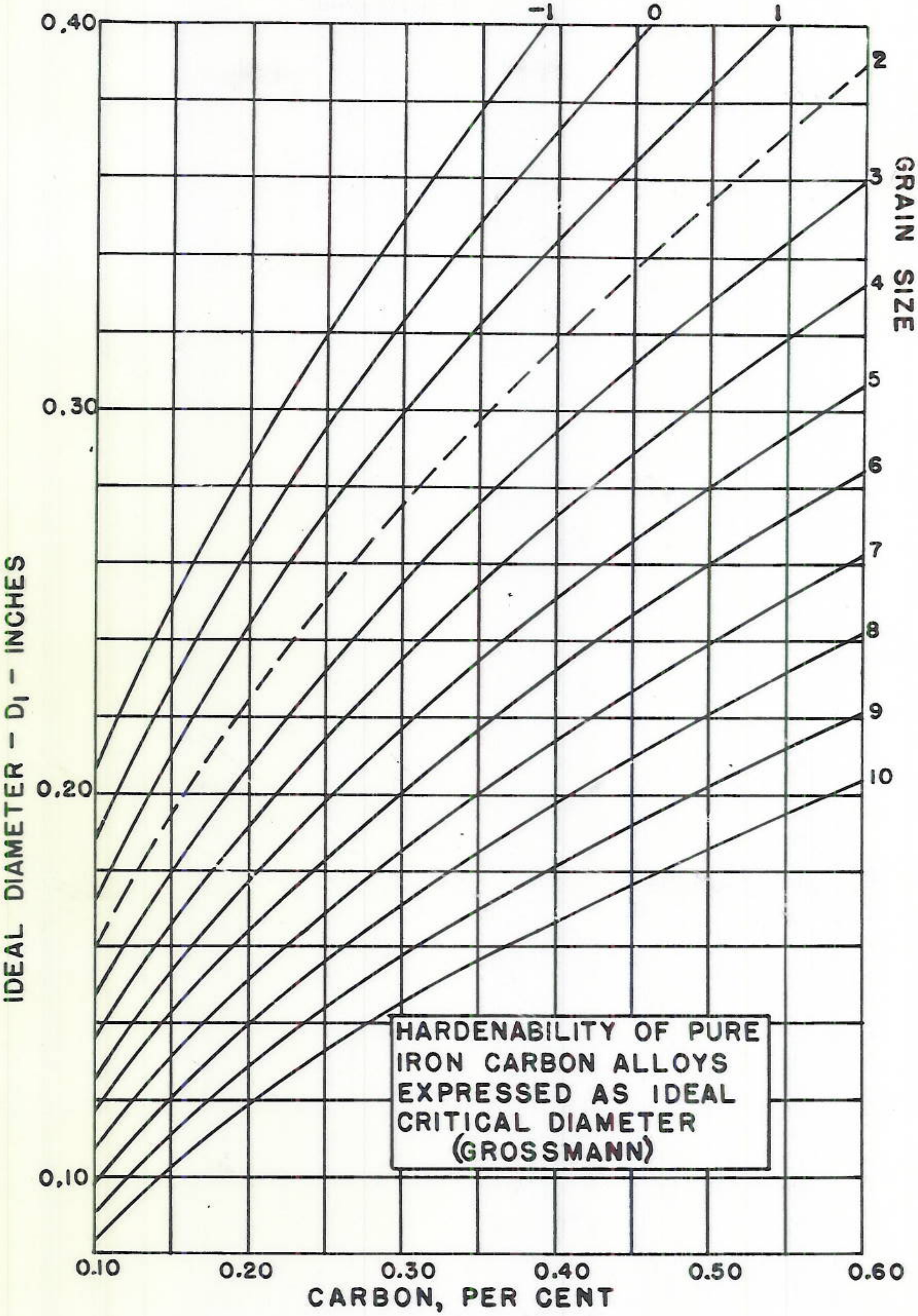

RELATION BETWEEN END-QUENCH HARDENABILITY BAR AND DIAMETER OF ROUND WITH IDEAL QUENCH
DIAMETER HAVING SAME CENTER HARDNESS WITH IDEAL QUENCH – D1 – INCHES
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1.0
1.2
DISTANCE FROM QUENCHED END – INCHES

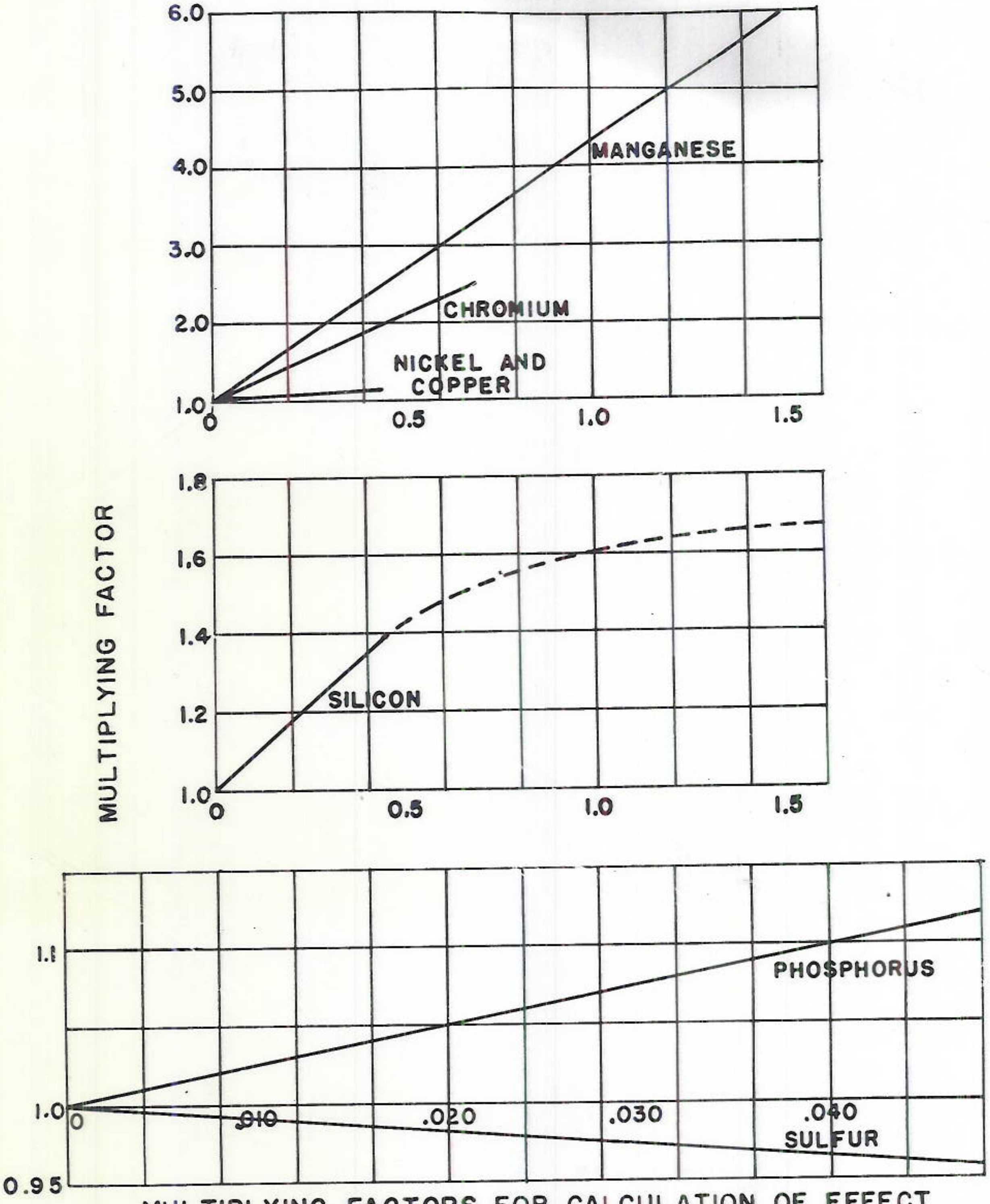
Plate 10



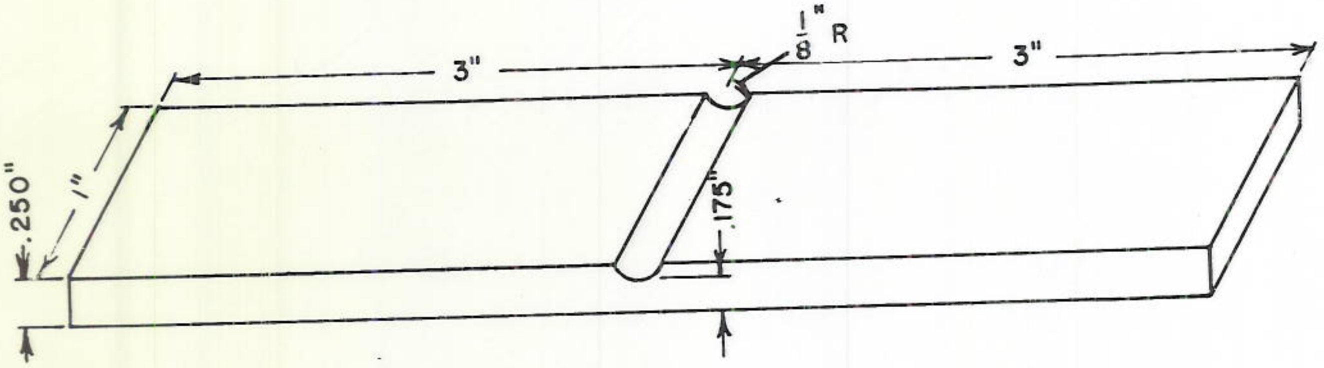
EFFECT OF GRAIN SIZE ON HARDENABILITY IN TERMS OF IDEAL DIAMETER, D_I (GROSSMANN)

PLATE II

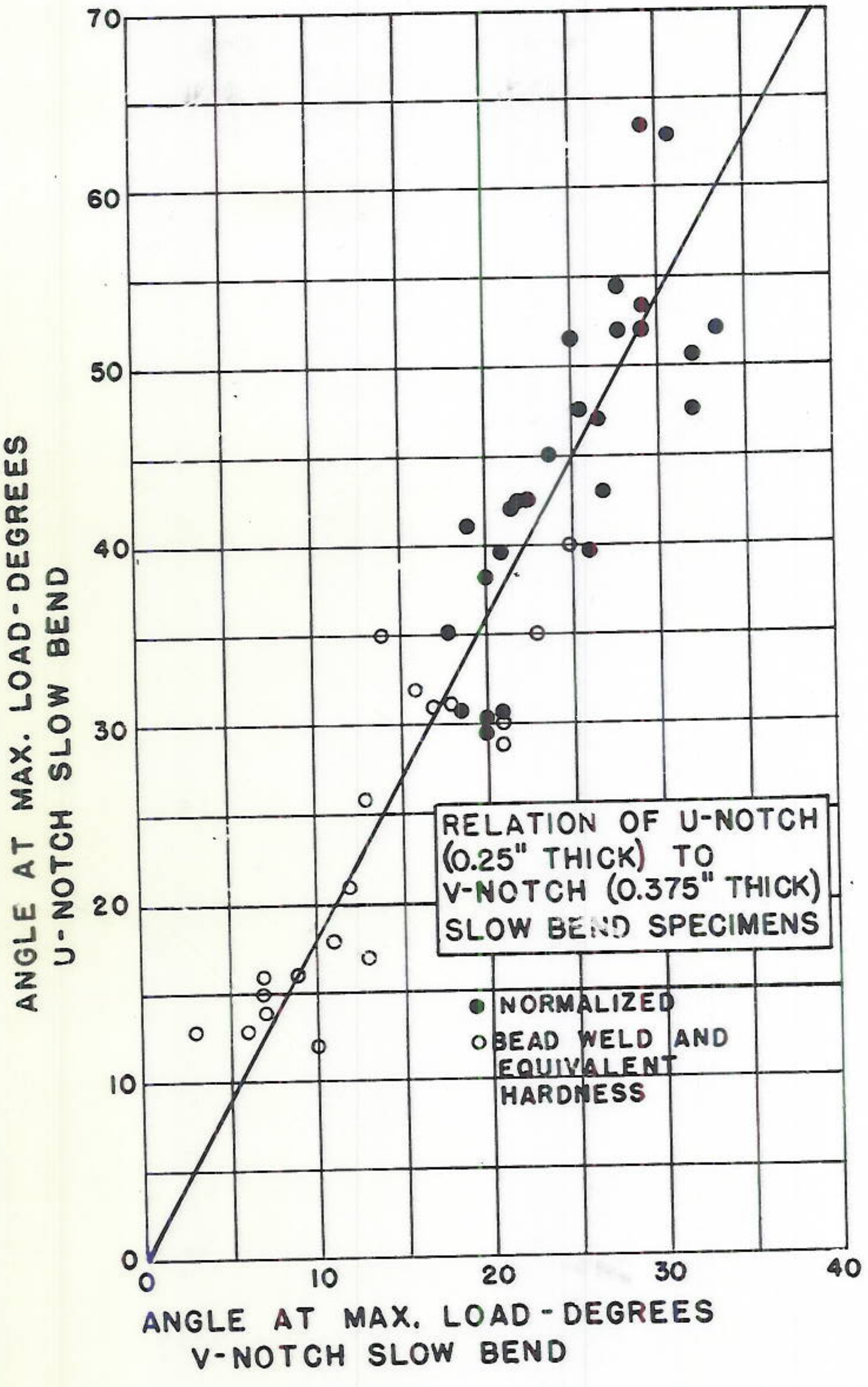

0.40
0.30
0.20
0.10
IDEAL DIAMETER - D_I - INCHES
0.10
0.20
0.30
0.40
0.50
0.60
CARBON, PER CENT
-1
0
1
2
3
4
5
6
7
8
9
10
GRAIN SIZE
HARDENABILITY OF PURE IRON CARBON ALLOYS EXPRESSED AS IDEAL CRITICAL DIAMETER (GROSSMANN)

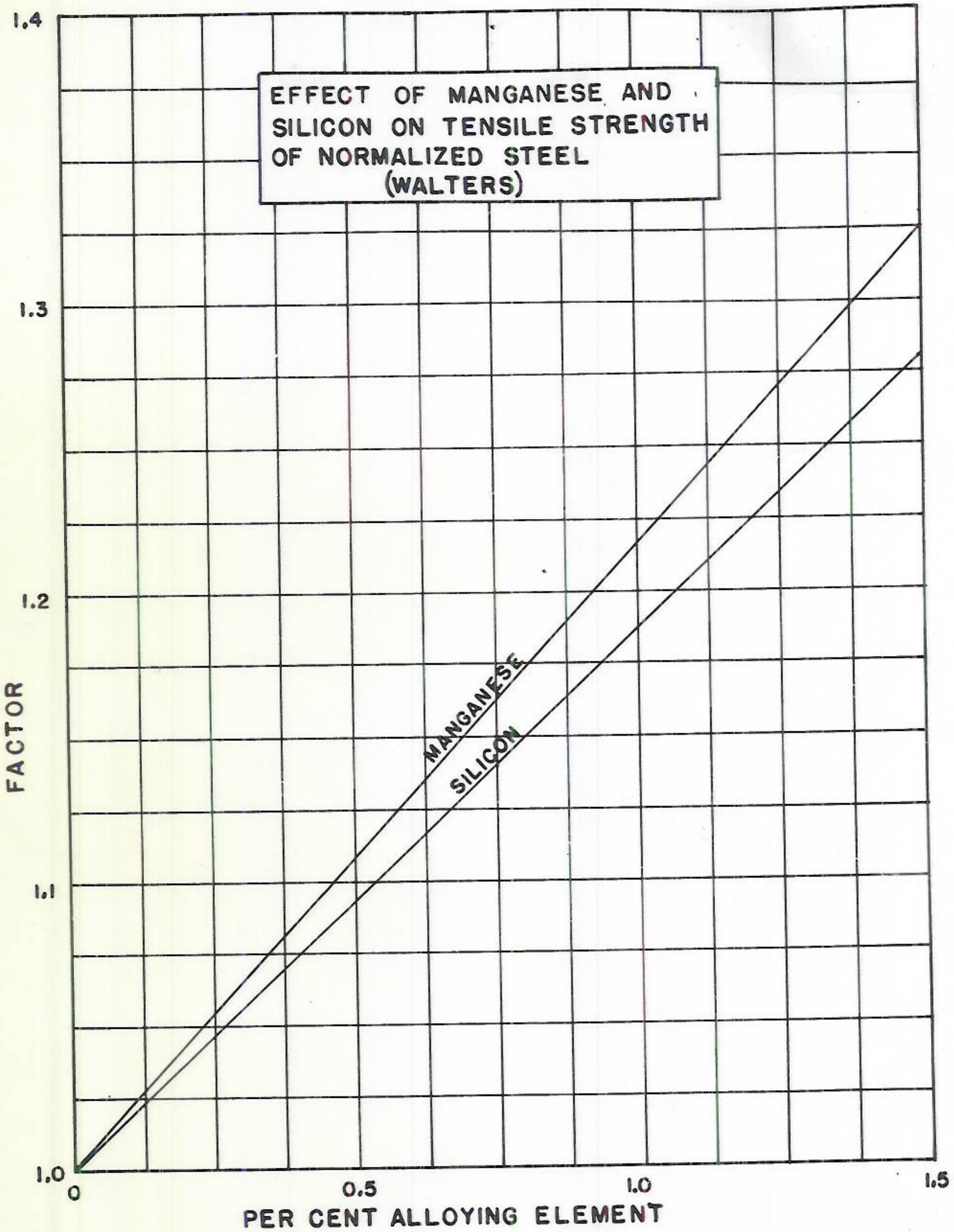


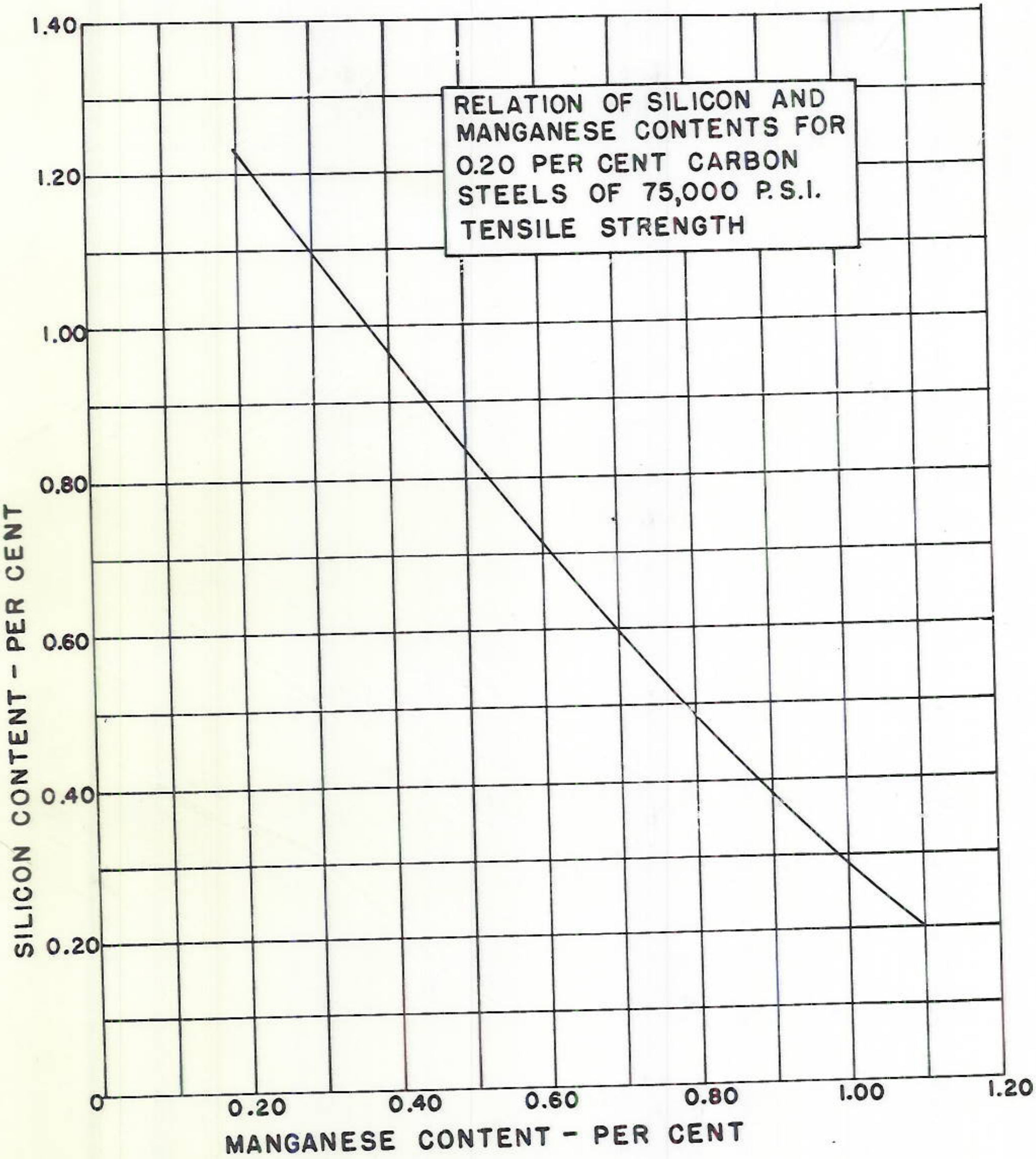
MULTIPLYING FACTORS FOR CALCULATION OF EFFECT OF VARIOUS ELEMENTS ON HARDENABILITY.
(GROSSMANN)

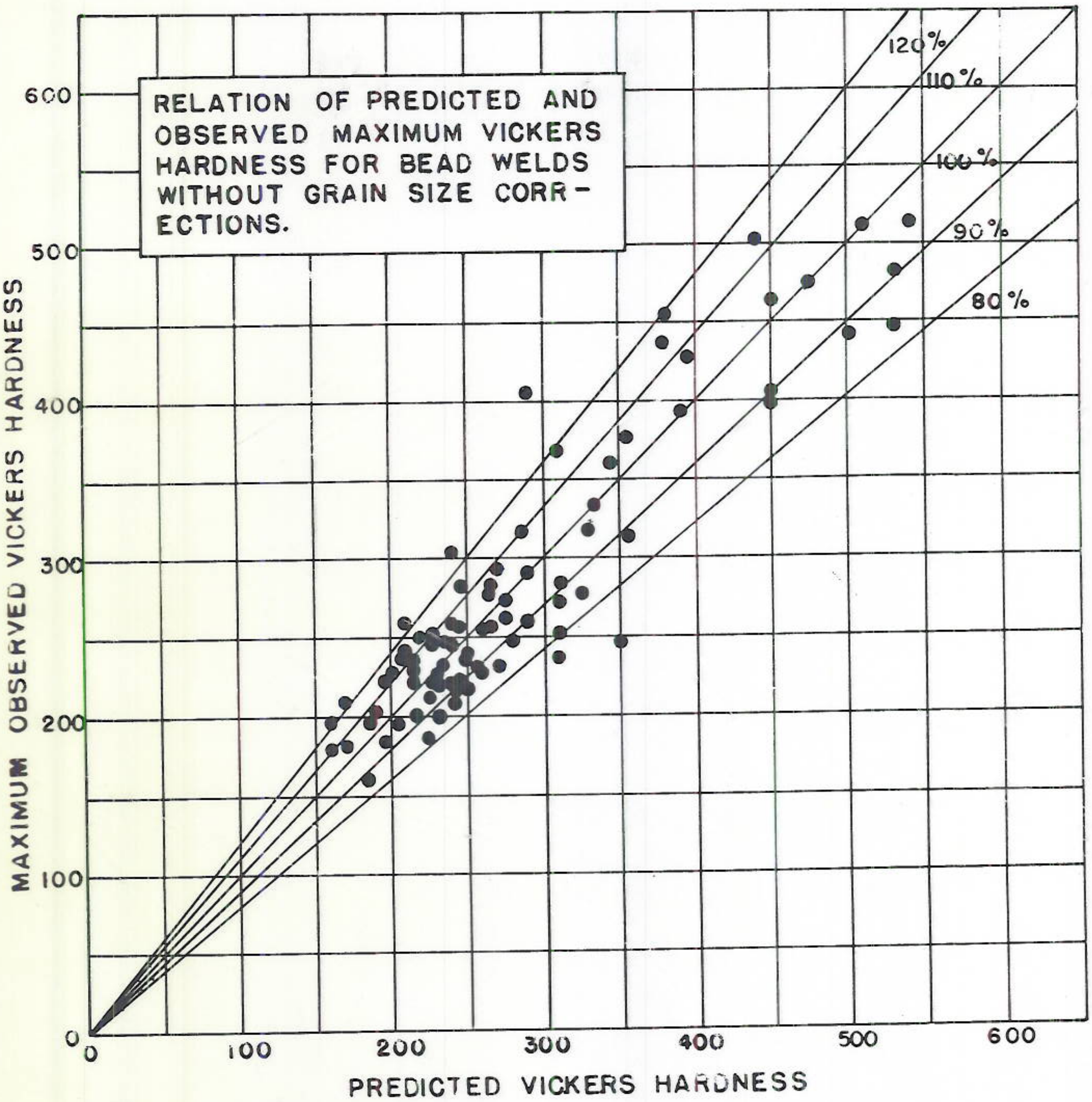


U-NOTCH SLOW BEND SPECIMEN


70
60
50
40
30
20
10
0
0
10
20
30
40
ANGLE AT MAX. LOAD-DEGREES
U-NOTCH SLOW BEND
ANGLE AT MAX. LOAD-DEGREES
V-NOTCH SLOW BEND
RELATION OF U-NOTCH (0.25" THICK) TO V-NOTCH (0.375" THICK) SLOW BEND SPECIMENS
● NORMALIZED
○ BEAD WELD AND EQUIVALENT HARDNESS

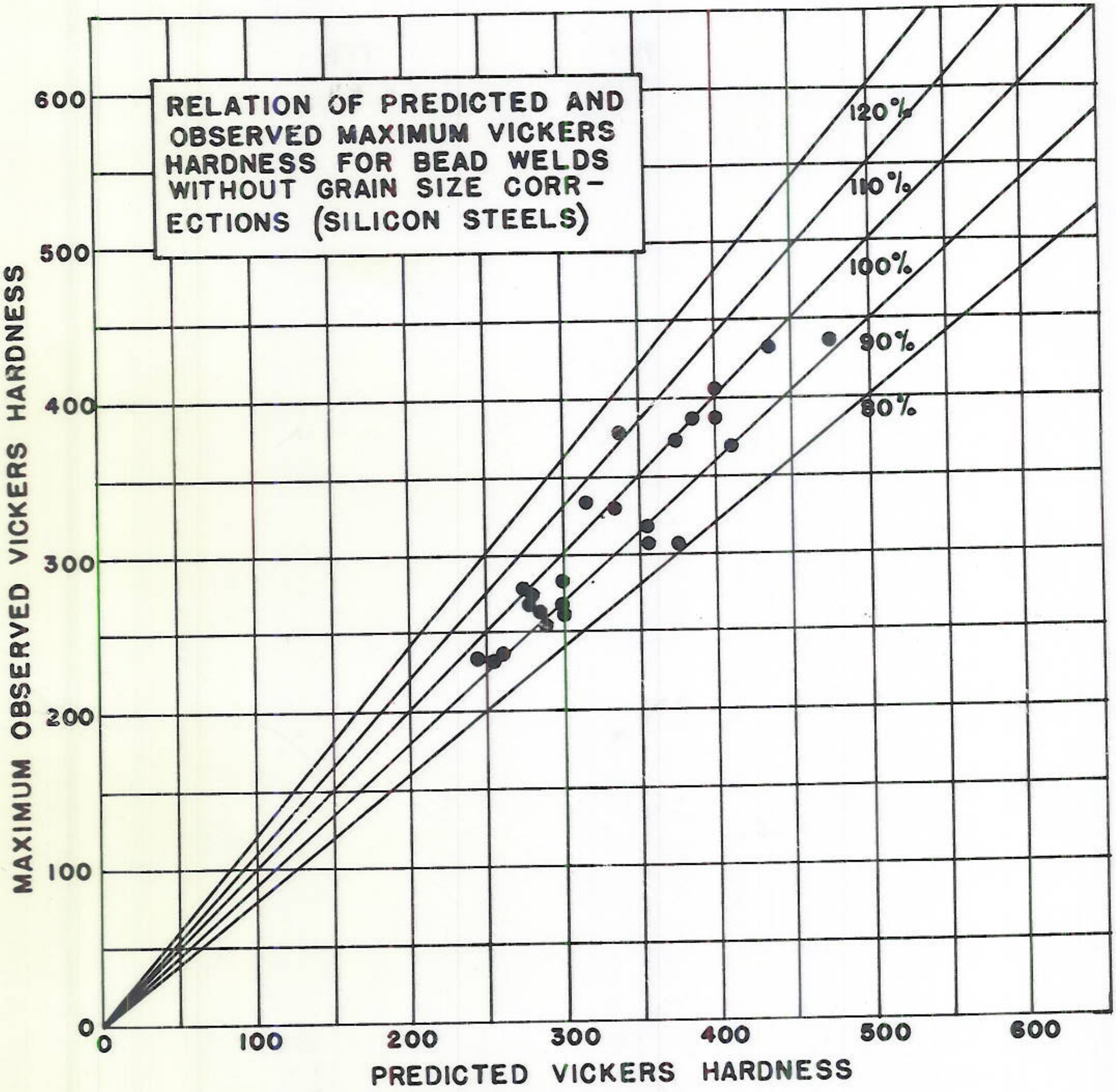

EFFECT OF MANGANESE AND SILICON ON TENSILE STRENGTH OF NORMALIZED STEEL (WALTERS)
1.4
1.3
1.2
1.1
1.0
FACTOR
MANGANESE
SILICON
0
0.5
1.0
1.5
PER CENT ALLOYING ELEMENT

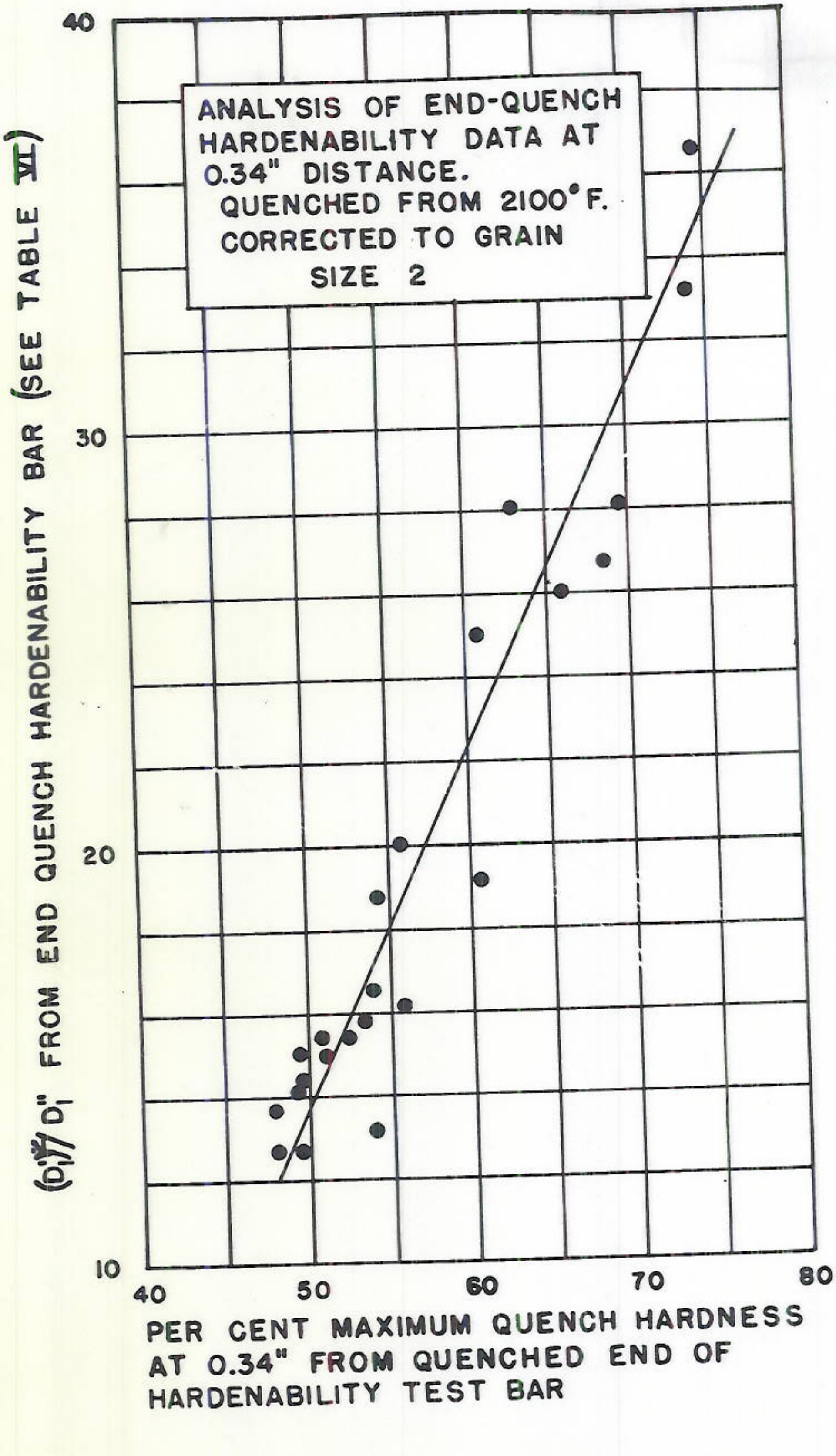

RELATION OF SILICON AND MANGANESE CONTENTS FOR 0.20 PER CENT CARBON STEELS OF 75,000 P.S.I. TENSILE STRENGTH
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0
SILICON CONTENT - PER CENT
0.20
0.40
0.60
0.80
1.00
1.20
MANGANESE CONTENT - PER CENT

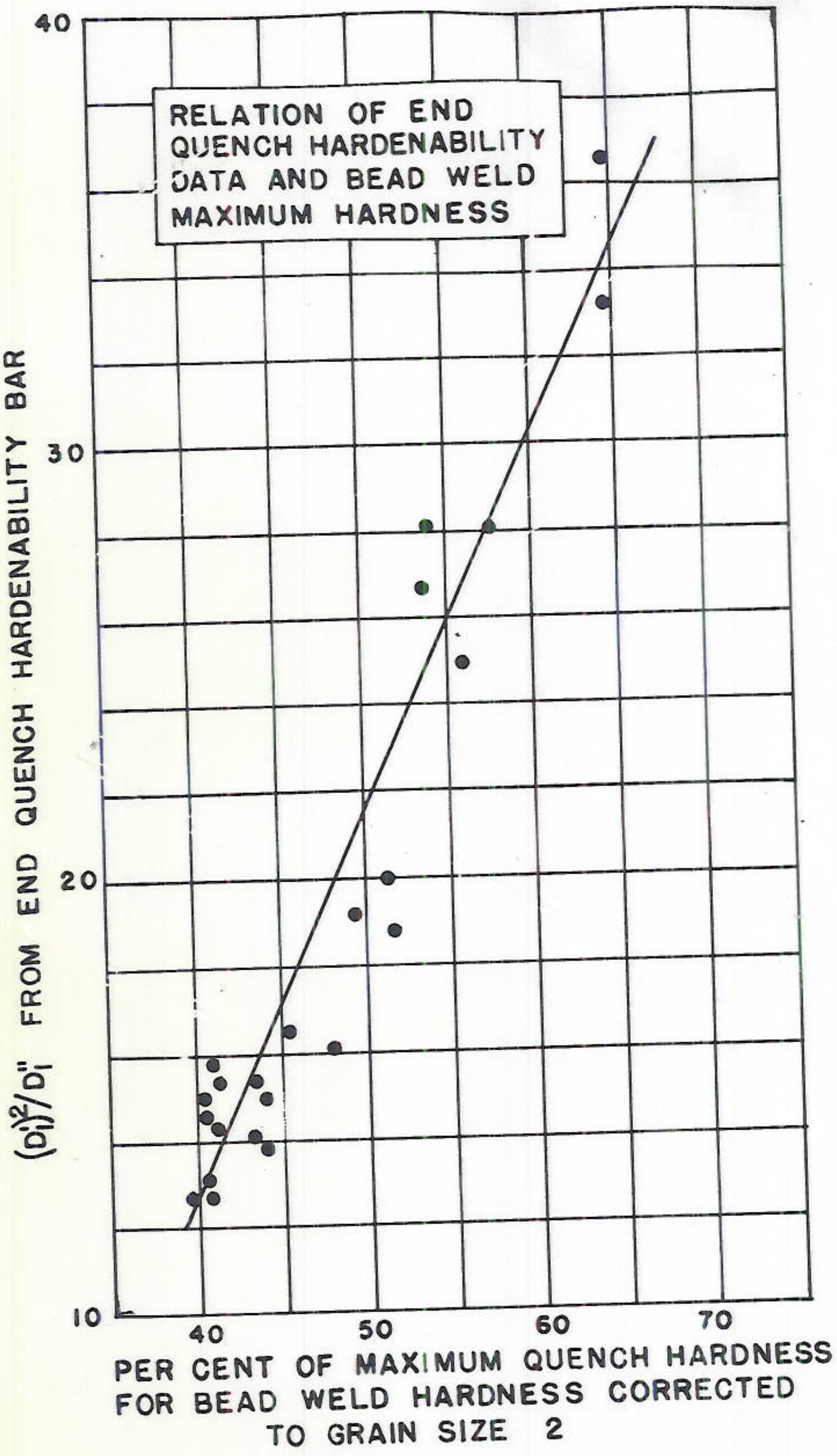


RELATION OF PREDICTED AND OBSERVED MAXIMUM VICKERS HARDNESS FOR BEAD WELDS WITHOUT GRAIN SIZE CORRECTIONS.

PLATE 18

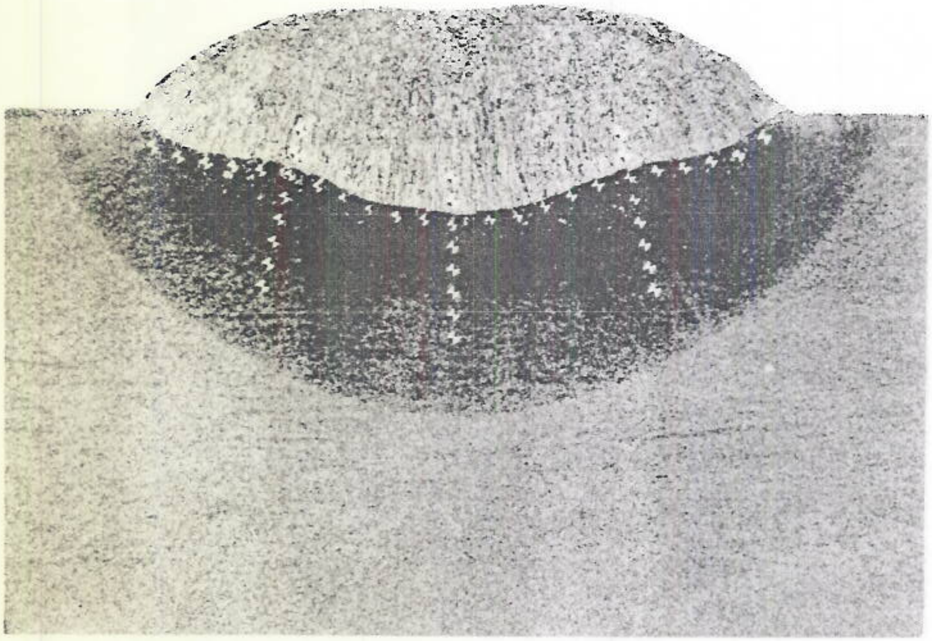

RELATION OF PREDICTED AND OBSERVED MAXIMUM VICKERS HARDNESS FOR BEAD WELDS WITHOUT GRAIN SIZE CORRECTIONS (SILICON STEELS)
120%
110%
100%
90%
80%
MAXIMUM OBSERVED VICKERS HARDNESS
PREDICTED VICKERS HARDNESS
0
100
200
300
400
500
600


ANALYSIS OF END-QUENCH HARDENABILITY DATA AT 0.34" DISTANCE.
QUENCHED FROM 2100° F.
CORRECTED TO GRAIN SIZE 2
$(D_I'')_Y / D_I''$ FROM END QUENCH HARDENABILITY BAR (SEE TABLE VI)
40
30
20
10
40
50
60
70
80
PER CENT MAXIMUM QUENCH HARDNESS AT 0.34" FROM QUENCHED END OF HARDENABILITY TEST BAR



RELATION OF END QUENCH HARDENABILITY DATA AND BEAD WELD MAXIMUM HARDNESS

PLATE 21



SECTION OF BEAD WELD
SHOWING HARDNESS SURVEY.