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Report on

Research on the Weldability of Iron Alloys
The Bead-Weld Nick-Bend Test for Weldability

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ABSTRACT

In a survey of the various methods of measuring weldability by determining the ductility of the heat affected zone, no direct method was found which was applicable to the study of the weldability of steels in all thicknesses. The bead-weld nick-bend test is a weldability test designed to measure the effect of a welding technique upon the ductility of the heat affected zone of a steel. A test procedure is presented together with a discussion of variables affecting the bead-weld nick-bend test. The test procedure gives reproducible results and requires a test specimen which can be easily prepared using only a hack saw. Tests can be made under conditions closely simulating those encountered in practice with regard to steel composition, thickness of plate, brand of electrode and welding techniques actually used.

effort to improve the accuracy of the test, hardness measurements using the Vickers method with 10 kg. load have replaced, for the most part, those obtained with the Rockwell C-scale. Within the past few years, the Knoop method of micro-hardness has found (2)(3) favor among some investigators for determining the maximum hardness in the heat affected zone. The maximum hardness method is quite flexible as it is possible to vary welding techniques and thickness of material over a wide range, although its success will depend entirely upon the indirect relationship of maximum hardness and ductility.

(B) T-Bend Test

7. The well known Navy T-bend test for determining weldability has been described by Ellinger, Bissell, and Williams (4). Specimens for this test are prepared from 1/4", 1/2" or 3/4" plates. T-bend specimens are cut from a welded assembly; each specimen is a T-strip measuring 1-1/4" in width taken perpendicular to the fillets of the T-section. A special jig is used for bending the specimens. The angle to which the base of the T is bent at maximum load is significant and is recorded together with data as to the load and type of fracture at failure. The T-bend test is a direct test which summarizes the quality of the steel as well as its weldability.

(C) Slow-Bend (V-Notched)

8. Considerable data have been presented by the Naval Research Laboratory using this test (2)(5)(6). All of the published data, however, have referred to tests on 1/2 inch plate. Single bead-welds are deposited transverse to the direction of rolling on plates 6 inches by 7 inches by 1/2 inch. Strips 1-1/2 inches wide are cut transverse to the direction of the bead-weld. Only sufficient metal is removed from the top surface to eliminate irregularities. Material is then removed from the lower surface to obtain a specimen 1.5 inches wide by 0.375 inch thick with the top and bottom surfaces finished by grinding. The specimens are etched in a 5 per cent nital solution and the V-notch is located so that the apex of the notch is machined tangent to the fusion line. The specimen is bent to failure in a qualification test jig and the angle at maximum load for each specimen is recorded. For comparison an identical specimen from the unaffected plate material is also made. The large amount of careful machining required has been a legitimate objection to this test for any investigation other than a research program.

(D) End-Quench Hardenability Test (Jominy)

9. It has been suggested by Kinzel (7) that each combination of welding conditions corresponds to a position on the end-quench hardenability bar. A very comprehensive investigation following this line of reasoning has been presented by Doan, Stout and Frye (8). Standard end-quench hardenability test specimens are heated to 2100°F to produce an enlarged austenitic grain size similar to that in the heat affected zone of a bead-weld. The bars are quenched in the standard manner and the hardness measured along the bar using the Vickers hardness method.

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(E) Slow-Bend (U-Notch) Continuous Cool

10. In order to use the end-quench hardenability test to measure the weldability of a steel, further information regarding the relation of hardness and ductility is required. A number of flat specimens (1 x 0.25 x 6 inches) are cooled at various rates from 2100°F by water and oil quenching, air and furnace cooling, and occasionally by other methods. These specimens are notched after heat treatment and the ductility measured by a slow-bend test. The angle at maximum load is measured and the hardness of each specimen is determined. From these data a relationship between hardness and ductility for a steel is determined and the ductility corresponding to the maximum hardness of a weld may be predicted. For homogeneous material the test can be roughly correlated with direct bend tests such as the T-bend and V-notched slow-bend specimens.

(F) Standard Qualification Tests and Workability Tests

11. In a full evaluation of any weldability test such as described above, a correlation with practical welded fabrication will be necessary. In the development of high-tensile low alloy steels other expedients such as the relationship of tensile strength to chemical composition (9) have also been found useful.

(G) Weld Cracking Tests

12. A number of tests which measure the cracking tendency of a steel or weld joint have been proposed by American as well as by British investigators. The chief cause of cracks in the heat affected zone is the hardening of the base metal accompanied by a loss in ductility; increased cooling rate, increased restraint, and hydrogen seem to be contributing factors. The tendency for cracking is generally reduced by preheating and by a high rate of heat input. A number of tests have been suggested; of these a macro or microscopic examination of bead-weld cross sections, or of the restrained fillet of the Reeves type (10), or some form of restrained joint have been found satisfactory by various investigators. Although considerable information is available it is still not possible to make a clear-cut analysis of the exact relationship of all causes of cracking.

(H) Miscellaneous

13. In an analysis of the effects of welding on a steel, a number of factors have been discussed from time to time. No simple relationship has been found between the hardenability of a steel as calculated from chemical composition or as measured by the end-quench hardenability test, and the hardness attained in the heat affected zone (6). A number of investigators have pointed out the importance of the critical cooling rate of a steel; those steels with a low critical cooling rate usually require special precautions in welding. The effect of cooling rate on transformation temperature has also been found important. Undoubtedly the direct application of the principles of metallurgical behavior which apply to ordinary heat treatment practices will not be possible with the higher temperatures and shorter intervals of time which accompany the welding cycle.

NARRATIVE OF ORIGINAL WORK AT THE LABORATORY

14. In a survey of the various methods of measuring the ductility of the heat affected zone, no direct method was found which was applicable to the study of steel in all thicknesses. Almost all of the test work has been on plate of less than one inch thickness, whereas difficulties in welding in general are less for the lighter weight material. Many attempts have been made (5)(11)(12) to study the ductility in the heat affected zone by preparing a specimen with a longitudinal bead-weld on the tension surface of the bend specimen. This type of specimen has not proved to be sufficiently critical for use with low alloy steels and has been found applicable mainly to medium alloy and aircraft steels. It was suggested to the authors that the use of a transverse bead-weld might restrict deformation sufficiently in bending the specimen that failure would result at the toe of the weld. With this in mind, specimens (Plate 1) were prepared for steels 1/2", 3/4", and 1" in thickness. The results of the bend tests are shown in Table 1. In all cases the deformation was not restricted sufficiently by the toe of the weld to make it possible to measure the effect of changes in welding technique on the ductility in the heat affected zone. As a result of these tests it appeared that the use of some type of notch would be necessary in order to restrict the deformation to a limited area in the heat affected zone.

BEAD-WELD NICK-BEND TESTS

15. Basically the bead-weld nick-bend test is an outgrowth of the V-notched slow-bend test. The slow-bend specimen has been modified so that a minimum of preparation is required and so that the full thickness of the plate is tested. The test specimen consists of a notched flat bar (Plate 2) with the notch (prepared by a hack saw) so located that it restricts the deformation to the mid-portion of the specimen when tested as a static bend. The notch stops short of the heat affected zone in order that initial deformation will occur in the weld metal and failure is caused by rupture of the low ductility metal in the heat affected zone. The angle at maximum load is used as an index of the behavior of the material. The results for the bead-weld specimens are compared with those for identical specimens prepared from the plate material.

PROCEDURE FOR NICK-BEND TEST FOR WELDABILITY

16. The nick-bend test is designed to measure the effect of a welding technique upon the ductility of the heat affected zone of a steel. The following procedure is outlined for thicknesses of one-half to one and a half inches:

(A) Preparation of the Specimen Assembly

(a) Dimensions

The specimen assembly for the nick-bend test shall conform to the dimensions given in Plate 3.

(b) Condition of Specimen Assembly

The plates to be welded shall be in the as-rolled condition. Mill scale or any foreign surface material shall be removed by shot or sand blasting or by effective wire brushing before welding. (Note (a))

(c) Temperature of Assembly Prior to Welding

The plates shall be at room temperature ($70^{\circ} \pm 5^{\circ}F$) when the welding is started. (Note (b))

(d) Welding Procedure

If possible, the welds shall be mechanically deposited with full automatic control; however, manual welding is permissible if no mechanical facilities are available. The electrode shall be perpendicular to the work which shall be in a horizontal position to insure an even string bead. The bead shall be deposited using welding conditions as follows:

175 amperes
26 volts - reversed polarity
6 inches per minute travel for machine welding (Note (c))
or
6 inches of bead shall be deposited with 9-1/4 inches of electrode for manual welding
Electrode classification E6010 AWS and ASTM Spec.
Navy Spec. Class 1, Grade 1
Mild Steel - Heavy Coated - 3/16 inch diameter

A second plate shall be welded using 12 inches per minute travel or 6 inches of bead shall be deposited with 4-5/8 inches of electrode.

(B) Preparation of Specimens

(a) Two bend specimens shall be removed from each weldment as shown in Figure 3 by sawing or milling, using a suitable coolant. A saw-cut or milled notch shall be located along the center line of the weld-bead transverse to the length of the specimen and entirely in the weld nugget to a depth of 3/64 inch below the original surface of the plate (Plate 3). A power hack saw with a saw blade having a kerf of 1/10 inch (0.72 inch thickness of blade) or a milling cutter 3/32 inch wide may be used.

(b) At least two unwelded plate specimens having the same dimensions as the weld specimen and having a notch of the same depth and width shall be prepared for comparison.

(C) Testing of Bend Specimens

(a) The pair of specimens prepared from the weldment shall be tested at room temperature. The interval of time between welding and testing shall be two days. (Note (d)) The specimen shall be bent with the

notch in tension in a 3/4 inch T-bend jig (span 9 inches). A plunger with a 1 inch radius nose shall be used for bending (Plate 4). The specimen shall be placed on the female member of the jig and so aligned that the center of the notch is in a straight line with the center of the plunger. The plunger shall be secured to the crosshead of a bending machine. The load is applied through the parts of the jig by the machine which may be a vertical screw or hydraulic type with a beam, dial or other suitable means for indicating and/or recording the loading characteristics. The downward feed of the plunger shall be continued until the angle of bending is 120° or until the specimen is carrying no appreciable load.

(D) Results of Nick-Bend Test

(a) The maximum load and the angle of bend at maximum load shall be recorded. If a stress-strain recorder is available, a record of the loading behavior as indicated by a stress-strain diagram shall be made. Typical data for this test are shown in Plate 5 and Tables 3 and 4. Typical specimens after test are shown in Plates 6 and 7.

(E) Notes

(a) Plates may be normalized or given other heat treatments if information for these plate conditions is desired.

(b) Plates may be at elevated or subnormal temperatures when welding is started if such information is desired. A refrigerated cabinet, a liquid medium or an oven are suggested for preparing subnormal and elevated temperature test plates.

(c) For further information, additional speeds of travel of 4, 8, and 10 inches per minute have also been used. Other types of electrodes may also be used.

(d) Additional information may be obtained using other testing temperatures and other intervals between welding and testing.

DISCUSSION OF VARIABLES AFFECTING THE BEAD-WELD NICK-BEND TEST

17. In the early testing using the bead-weld nick-bend test consistent performance could not be obtained although the agreement of duplicate specimens welded at the same time and tested consecutively was excellent. Upon further study, it was noted. that there was a gradual increase in ductility of the bead-weld nick-bend specimen as the time interval between welding and testing became greater. For example (Plate 8) the bend-ductility of steel #367 increased from 13-1/2 degrees one day after welding to 45 degrees at 34 days after welding. This phenomenon was noted for all steels tested (Plate 9). No entirely satisfactory explanation has been forthcoming, although it is felt that the increase in ductility may be caused by a relaxation or redistribution of the welding stresses in the weld metal and heat affected zone.

18. It is important to remember that ductility is affected by the time interval between welding and testing in order to be able to determine the effect of other variables in this and other tests of welded

joints. Practically, it is fortunate that the change in ductility is toward the improvement of the weldment. This gives further evidence to support the statement often made that if a weldment is sound when fabrication is complete, the chances for continued satisfactory performance are good.

19. The weld-ductility appears to be sensitive to the temperature at which the specimen is maintained between welding and testing. To determine the effect of temperature a number of specimens were stored in an oven between welding and testing. A decided increase in ductility (Table 5) was noted for specimens maintained at 85°C (185°F), 100°C (212°F) and 200°C (392°F). If the increase in ductility is a phenomenon of relief of stresses, such an increase in ductility is to be expected. It is interesting to note that the deposition of a second bead upon the first bead resulted in little or no change in the time-ductility relation observed for single bead-weld tests (Table 6).

20. To study the effect of the type of electrode used for the nick-bend test, specimens were prepared using 25-20 Cr-Ni austenitic electrodes. No change was observed in the ductility (Table 7) as the angle at maximum load had reached a constant value for the tests performed at the end of one day. It is expected that other types of electrodes, different from the AWS E6010 used for most of the present tests, will affect the time-ductility relationship. It is also expected that the tendency toward cracking under restraint for a particular steel and electrode will be greater for those combinations which show low nick-bend ductility shortly after welding.

21. In order to determine the care which must be taken in preparing the nick-bend specimen with a hack saw, several modifications of the notch were made. Specimens were welded from a number of steels and notches were milled so as to determine the effect of depth and width of the nick on the ductility of the specimen. A change in the depth of the notch from 1/32" to 1/16" shows a slight effect (Plate 10). A change in the width of the notch from 1/16" to 1/4" slowly increases the angle obtained for the steels tested (Plate 11). It is felt that accuracy sufficient for the nick-bend test is obtained using a hack saw for preparation of the notch.

22. The question has often been raised regarding the validity of using the angle of bend at maximum load for evaluating the energy absorption of a bend specimen. An evaluation of the energy absorbed by a test specimen, in the bend test, may be obtained from the stress-strain record. The area under the stress-strain diagram may be expressed in inch-pounds and compared with the angle at maximum load. Such a comparison using 51 specimens is presented in Plate 12. The angle at maximum load is found to be related (within the accuracy required) to the energy absorbed except for angles over approximately 55°. As few of the weld specimens were sufficiently ductile to give angles in excess of 50°, it is felt that the angle at maximum load is indicative of the energy absorbed in the nick-bend test.

23. A number of tests were performed to determine the effect of the ratio of the diameter of the plunger used in the testing jig. Plungers of 1, $1\frac{1}{2}$, 2 and 3 inch diameter were used in tests with two steels (Table 8). The diameter of the rollers was maintained at 3" with a 9" span between centers. Very little effect was detected, although in one series of tests the ductility is greatest with the 3" diameter plunger. This does not follow in the second steel, as the ductility is lowest for the 3" diameter plunger. It was decided to use the largest plunger which gave consistent results; thus, all other tests reported here are made with the 2" diameter plunger and the 3" diameter rollers with a span between centers of 9".

24. The question of reproducibility must always be considered in the development of any new test. In many of the tables that are presented in this paper, the results of duplicate test specimens have been reported in order to give evidence of the reproducibility of the test (Tables 5 and 8). In general, the agreement is excellent. There are some cases, however, in which the results of duplicate specimens are not in good agreement. An examination of these specimens often revealed causes such as unsound metal or improper notching. Specimens which are tested shortly after welding show a tendency for greater discrepancies than those held for greater lengths of time after welding. Satisfactory reproducibility is shown for the results of the five identical test plates reported in Table 9.

25. An attempt was made to prepare specimens so that they could be tested less than 1 day after welding. Strips were cut $1\frac{1}{2}$" wide and four sections clamped together edgewise. Welding was then performed in accordance with standard procedure. As soon as welding was completed, the specimens were unclamped and broken apart, notched, and then were ready for testing. The results of such a testing procedure in many cases compared favorably with those welded in the larger standard section. However, in general, the results were not as consistent and could not be relied upon to give as uniform results as those welded using the 6" wide plate. Further data will be required before definite conclusions can be drawn.

26. If a test is to be satisfactory, it is desirable that the ductility will be affected by changes in welding technique. The area of penetration may be maintained reasonably constant by using uniform current and arc length; a range in speed of travel from 4 to 12 inches per minute may be used to vary the power level of the welding technique. Such tests made on a number of steels (Plate 13) showed a decrease in ductility as measured by the nick-bend test for an increase in speed of travel. In other words, ductility increases as the power input increases.

27. The relation of thickness and power input was determined on three steels of 2 and 2-3/4 inches thickness re-rolled to $1\frac{1}{2}$", 1", 3/4", and 1/2" thicknesses. These steels were normalized and nick-bend specimens prepared. The results for one of these steels #423 are shown in Plate 14. For a given power input, ductility increases as the plate thickness decreases. A plot of the power input per unit thickness is presented in Plate 15 for the nick-bend tests on steel #423. The speed of travel in inches per minute is indicated for each of the points plotted. In general, the higher rates of travel show better ductility per unit power input than

is obtained for the same power input with a slower rate of travel. This indicates that the speed of travel is effective not as the first power but rather as some fractional power. Considerable additional investigation will be required to establish exactly the fractional power that will best represent the heat transferred to the plate by the welding arc. From the information that is now available the effective power input varies approximately as the 4/10 power of the speed of travel expressed in seconds per lineal inch. Hence the scatter of the data in Plate 15 will be reduced considerably if the following empirical equation is used:

$$H = \frac{EI(S)^{4/10}}{T}$$

where H = effective power input
E = arc length in volts
I = arc current in amperes
S = speed of travel in seconds per lineal inch
T = thickness in inches

Using the above relation the data for steel #423 shown in Plate 15 is again presented in Plate 16. Further tests to establish the validity of the above relation are shown for steels #312 and 340 in Plates 17 and 18.

28. In order to avoid the variation in plate hardness which results from normalizing the steel in ½ to 1½ inch thickness, two of the steels which were fairly uniform in hardness and macrostructure through the thickness were shaped to ½, 3/4, 1, 1¼, and 1½ inch thickness. These specimens were prepared from a 2-inch thick plate with only a clean up cut being taken on the one surface and the excess metal removed from the other surface. In this manner it was possible to weld on the first surface and hence the bead-weld was located at approximately the same level in the original plate for all thicknesses of specimens. Nick-bend specimens were prepared for all the shaped plates in accordance with the standard procedure. The relationship between the ductility of the welded specimens and the power input per inch of thickness (Plates 19 and 20) was obtained from these results. The ductility observed in these tests on as-rolled material was somewhat lower than that for the same steels tested in the normalized condition (Plates 17 and 18).

SUMMARY

29. A test procedure has been proposed for measuring the effect of a welding technique upon the ductility of the heat affected zone of a steel. The test procedure is reproducible and requires a test specimen which can be easily prepared using only a hack saw. Tests can be made under conditions closely simulating those encountered in practice with regard to steel composition, thickness of plate, brand of electrode, and welding techniques actually used. Results that are obtained have sufficient sensitivity to be a useful index. The effect of test variables has been studied and many variables such as the depth of notch and width of notch have shown satisfactory leeway for the usual shop practice.

30. For all steels discussed in this report, it has been shown that one of the variables that must be controlled is the time between welding and testing. It is fortunate, indeed, that the ductility of a welded specimen tends to improve as this gives a basis for further confidence in welded structures. Several cases have been encountered in which the nick-bend specimens welded at one time and tested at increasing time intervals, have changed from a brittle to a ductile type of failure. Some evidence is given that the relaxation or increase in ductility may be affected by such differences in temperatures as are encountered in summer and winter seasons. The effects of welding the nick-bend specimen at room or low temperatures and testing at low temperatures have not been investigated.

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TABLE 1 - TRANSVERSE BEAD-BEND RESULTS (SEE TABLE 2 FOR CHEMICAL COMPOSITION)

Steel	Thickness	Welding Technique	Angle at Max. Load	Max. Load	Angle at Failure
	Inches		Degrees	Pounds	Degrees
274	1/2	As Rolled Plate-Longitudinal	117	13,100	180
		Specimen 1½ in. wide	119	13,500	180
274	1/2	77 amps-22 volts-6 in./min.	78	12,500	115
		1/8 in. E6010 Electrode	72	12,100	118
274	1/2	90 amps-22 volts-6 in./min.	77	12,900	116
		1/8 in. E6010 Electrode	82	13,100	112
274	1/2	112 amps-21½ volts-6 in./min.	77	13,000	110
		1/8 in. E6010 Electrode	64	12,500	64
313	3.4	As Rolled Plate-Longitudinal	99	9,150	180
		Specimen 1½ in. wide	94	9,200	180
313	3/4	90 amps-22½ volts-6 in./min.	74	8,600	134
		5/32 in. E6010 Electrode	71	8,700	138
313	3/4	115 amps-22 volts-6 in./min.	67	9,150	146
		5/32 in. E6010 Electrode	67	9,200	156
313	3/4	133 amps-22½ volts-6 in./min.	68	9,600	120
		5/32 in. E6010 Electrode	68	9,450	130
314	1	As Rolled Plate-Longitudinal	83	15,700	180
		Specimen 1½ in. wide	88	15,000	180
314	1	90 amps-22½ volts-6 in./min.	61	15,750	130
		5/32 in. E6010 Electrode	75	15,750	129
314	1	115 amps-22½ volts-6 in./min.	74	15,900	163
		5/32 in. E6010 Electrode	74	15,900	176
314	1	133 amps-22½ volts-6 in./min.	74	15,400	165
		5/32 in. E6010 Electrode	74	15,900	156

ABLE 2 - CHEMICAL COMPOSITION IN PERCENT OF STEELS USED IN THIS INVESTIGATION

teel	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	V	Ti	Al
274	.18	1.02	.27	.019	.034	.16	.036	----	.24	.08	----	----
312	.19	1.48	.25	.035	.020	.13	.05	.03	.19	.003	<.010	.02
313	.16	1.01	.21	.023	.030	.21	.06	.03	.20	.075	<.010	.01
314	.18	1.10	.16	.018	.020	.11	.03	.02	.23	.003	<.010	.01
333	.18	1.09	.16	.017	.022	.12	.04	.025	.22	----	----	.015
334	.17	1.10	.17	.018	.024	.12	.04	.018	.22	.000	----	.025
340	.26	.40	.005	.022	.026	.10	.01	.04	.19	----	----	----
344	.22	1.52	.23	.025	.035	.13	.15	.05	.14	.012	.024	.01
367	.16	1.16	.26	.019	.027	.08	.05	.02	.19	.090	----	.02
369	.18	.69	.18	.016	.027	.147	.05	.04	.94	----	----	.01
391	.16	1.26	.24	.020	.020	.06	.04	.038	.15	<.010	<.010	.012
392	.14	1.10	.25	.025	.019	.26	.08	.025	.20	<.010	<.010	.014
393	.16	1.26	.21	.015	.024	.13	.12	.10	.13	.002	.005	.018
394	.16	1.31	.23	.030	.025	.03	.20	.005	.04	----	.025	.026
395	.14	1.27	.23	.031	.025	.03	.20	.005	.03	----	.035	.039
396	.17	1.34	.23	.018	.025	.10	.19	.005	.01	----	.030	.026
20	.23	.50	.003	.010	.053	.10	.05	.02	.15	----	----	.01
23	.18	1.17	.25	.024	.024	.185	.17	.017	.25	.080	.005	.02

TABLE 3 - DATA SHEET OF NICK-BEND TEST

Steel #314	Angle at Max. Load Degrees	Maximum Load Pounds
Plate	77 (No complete	15,400
	70 failure)	15,400
Bead-Weld		
A-2 days	26 (Sharp	13,150
after welding	25 failure)	13,350
175-26-6*		
B-2 days	13 (Sharp	10,700
after welding	19 failure)	11,900
175-26-12*		

*Amperes - Volts - Travel inches per minute

TABLE 4 - NICK-BEND TEST RESULTS (NORMALIZED) STEEL NO. 423

Thickness Inches	Welding * Technique	Angle at Maximum Load Degrees	Maximum Load Pounds
1/2	Plate	68	3,850
	175-26-4	62	4,175
	175-26-6	62	4,600
	175-26-8	58	4,300
	175-26-10	43	3,800
3/4	Plate	65	9,500
	175-26-4	37	9,750
	175-26-6	45	10,100
	175-26-8	32	9,360
	175-26-10	28	9,000
1	Plate	60	18,600
	175-26-4	34	18,600
	175-26-6	29	17,200
	175-26-8	26	16,600
	175-26-10	22	15,500
	175-26-12	20	15,000
1-1/4	Plate	75	22,150
	175-26-4	18	28,750
	175-26-6	18	22,200
	175-26-8	21	23,600
	175-26-10	19	26,000
1-1/2	Plate	65	30,400
	175-26-4	12	44,200
	175-26-6	24	35,000
	175-26-8	9	28,400
	175-26-10	13	30,900

* Amperes - Volts - Travel inches per minute

TABLE 5 - EFFECT OF TEMPERATURE OF STORAGE ON NICK-BEND RESULTS

Steel	Storage Time Days	Temp. 85°C (185°F) Angle at Max. Load Degrees	Temp. 85°C (185°F) Max. Load Pounds	Temp. 100°C (212°F) Angle at Max. Load Degrees	Temp. 100°C (212°F) Max. Load Pounds	Temp. 200°C (392°F) Angle at Max. Load Degrees	Temp. 200°C (392°F) Max. Load Pounds
314	1	41	14,200	56	15,700		
	2			45	15,300		
	3	58	15,200	54	15,500		
	4			48	15,300		
	5			60	15,800		
	6	50	14,700				
	14	59	15,400				
367	1	44	19,100				
	3	45	18,700				
	6	49	19,000				
	14	57	19,900				
395	1					39	16,800
	2			41	16,600		
	6			46	16,800		
420	1			45	13,800	46	13,650
	2			60	14,400		
	3			65	14,000		
	4			60	14,600		
	5			64	14,300		

TABLE 6 - EFFECT OF DOUBLE BEAD-WELD ON NICK-BEND DUCTILITY (STEEL #395)

	Double Bead		Single Bead	
Storage Time Days	Angle at Max. Load Degrees	Max. Load Pounds	Angle at Max. Load Degrees	Max. Load Pounds
1	21	14,250		
	19	14,100		
2	32	16,200	31	16,000
	35	16,500	32	15,900
5	40	16,950	38	16,700
	36½	16,700	46	17,400
10	57	17,500		
	43	16,800		

175 Amps. 26 Volts. 6 in./min. E6010 - 3/16" diameter electrode.

TABLE 7 - EFFECT OF 25-20 CR-NI ELECTRODE ON NICK-BEND DUCTILITY (STEEL #395)

Storage Time Days	Angle At Max. Load Degrees	Angle At Max. Load Pounds
1	56	17,000
	56	17,100
2	58	17,400
7	58	17,300
	55	17,500

175 Amps. 26 Volts. 6 in./min - 3/16" diameter - 25-20 Cr-Ni electrode.

TABLE 8 - EFFECT OF DIAMETER OF PLUNGER OF TESTING JIG

Steel	Diameter Of Plunger Inches	Angle At Max. Load Degrees	Max. Load Pounds
367	1	38	18,500
		29	17,500
2 days after welding	1½	34	18,100
		34	17,900
	2	35	17,800
		33	17,900
	3	39	18,300
		49	19,300
420	1	59	14,000
		51	14,100
2 days after welding	1½	52	14,150
		54	14,500
	2	58	13,200
		51	13,400
	3	52	14,250
		53	14,500
	1	57	14,000
		51	13,900
5 days after welding	1½	53	13,400
		58	14,000
	2	54	14,000
		54	14,000
	3	49	14,200
		44	13,350

175 Amps. 26 Volts. 6 in./min. E6010 - 3/16" diameter electrode

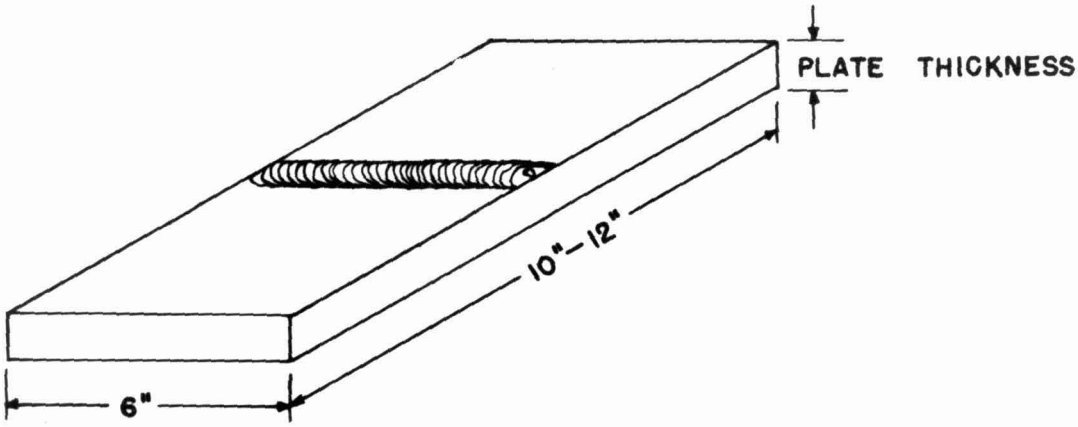
TABLE 9 - REPRODUCIBILITY OF NICK-BEND TEST FOR STEEL #314

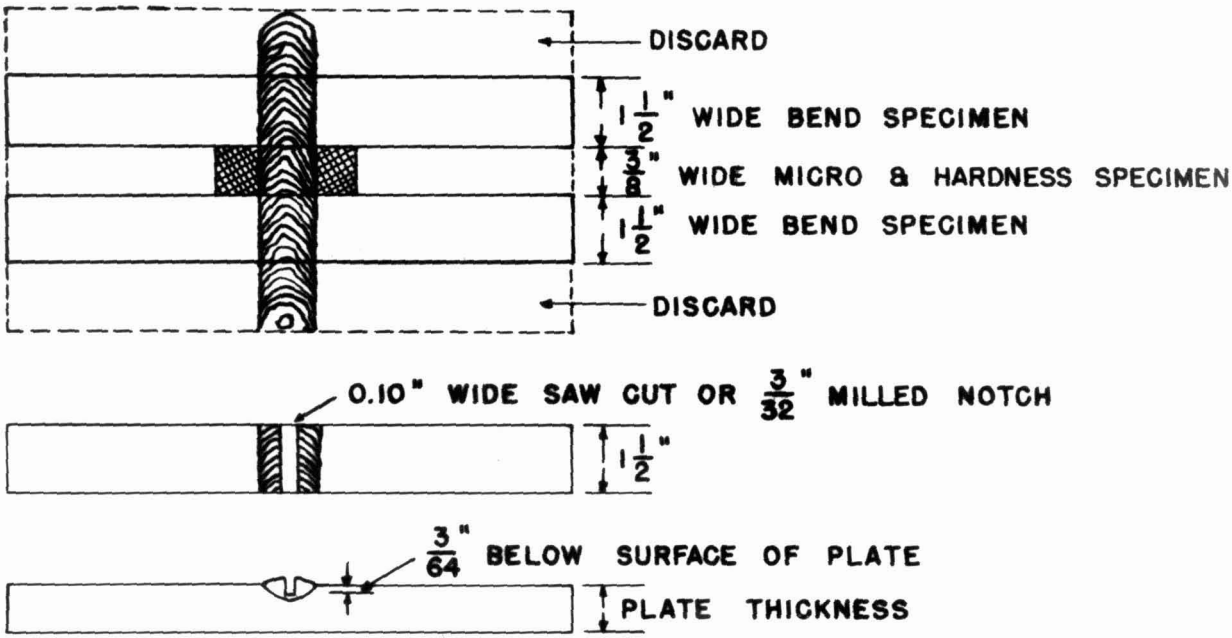
Angle at Max. Load Degrees	Max. Load Pounds
57	14,700
54	14,500
52	14,600
49	14,600
55	14,600
60	14,700
55	14,900
59	14,700
56	14,600
52	15,100
52	14,500
54	15,100
—	—
AVERAGE 55	14,700

175 Amps. 26 Volts. 6 in./min. E6010 - 3/16" diameter electrode

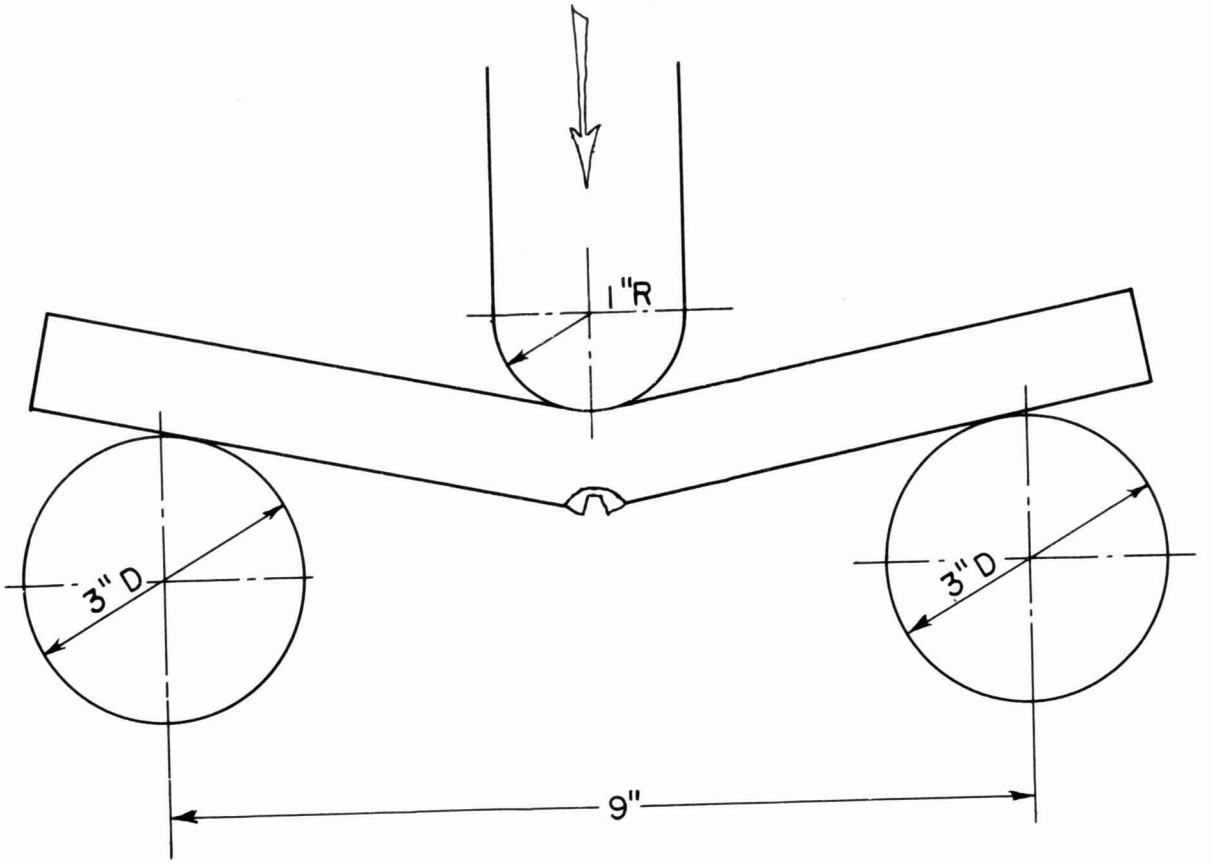
PLATE I

214060





BEAD-WELD NICK-BEND TEST SPECIMENS



TESTING JIG (SCHEMATIC)

PLATE 4

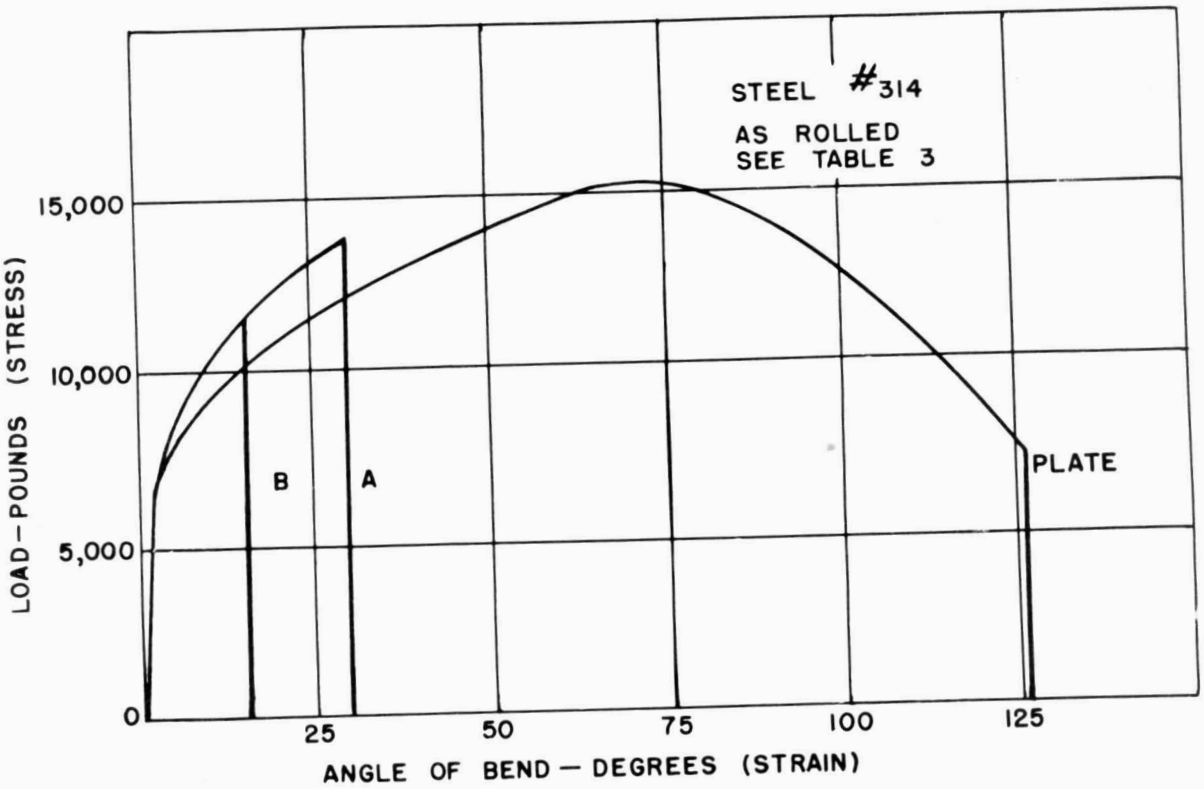
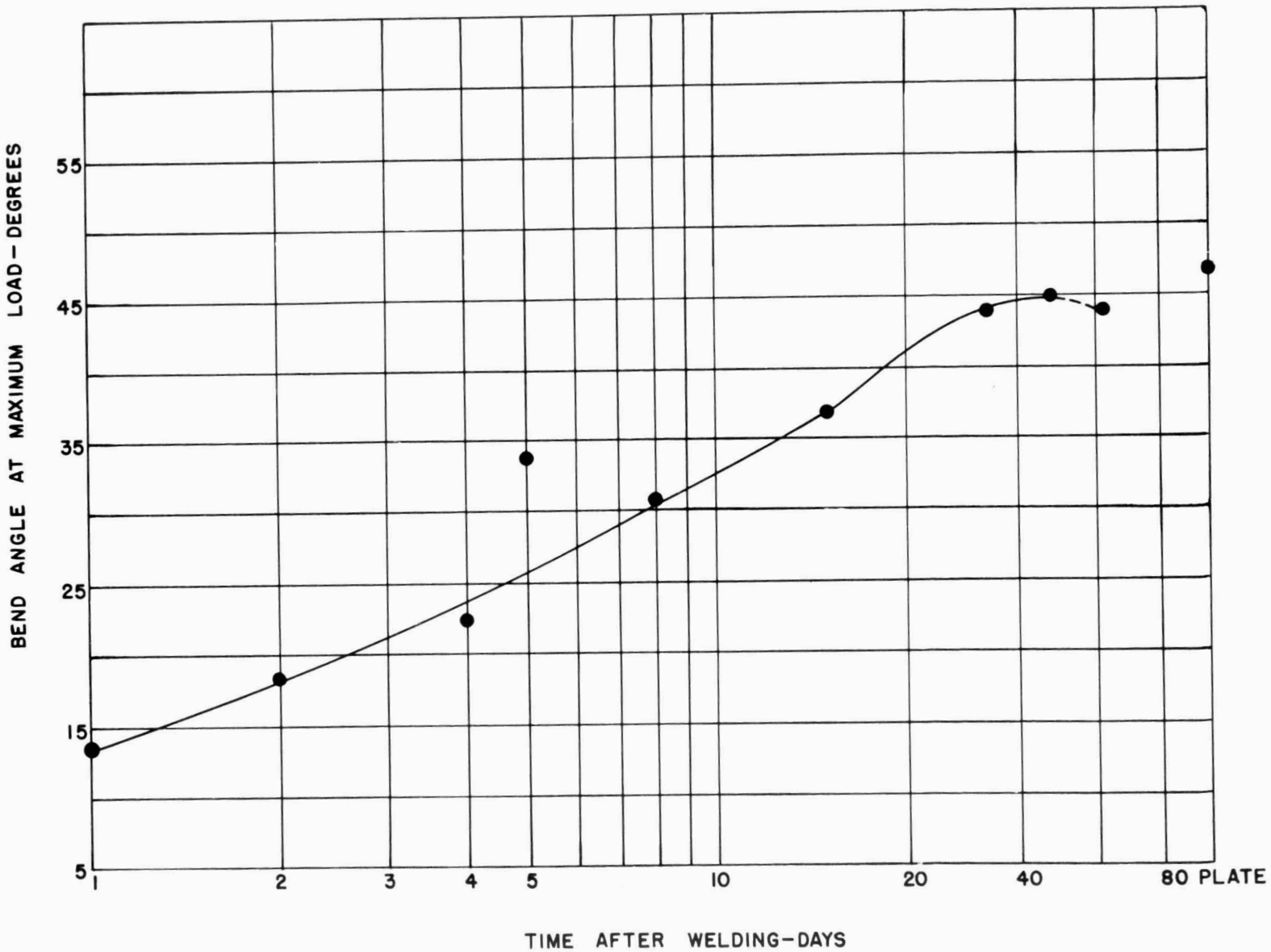

STEEL #314
AS ROLLED
SEE TABLE 3
15,000
10,000
5,000
0
LOAD-POUNDS (STRESS)
B
A
PLATE
25
50
75
100
125
ANGLE OF BEND — DEGREES (STRAIN)

PLATE 5

PLATE NICK-BEND SPECIMENS

PLATE 7


BEND ANGLE AT MAXIMUM LOAD-DEGREES
55
45
35
25
15
5
1
2
3
4
5
10
20
40
80 PLATE
TIME AFTER WELDING-DAYS

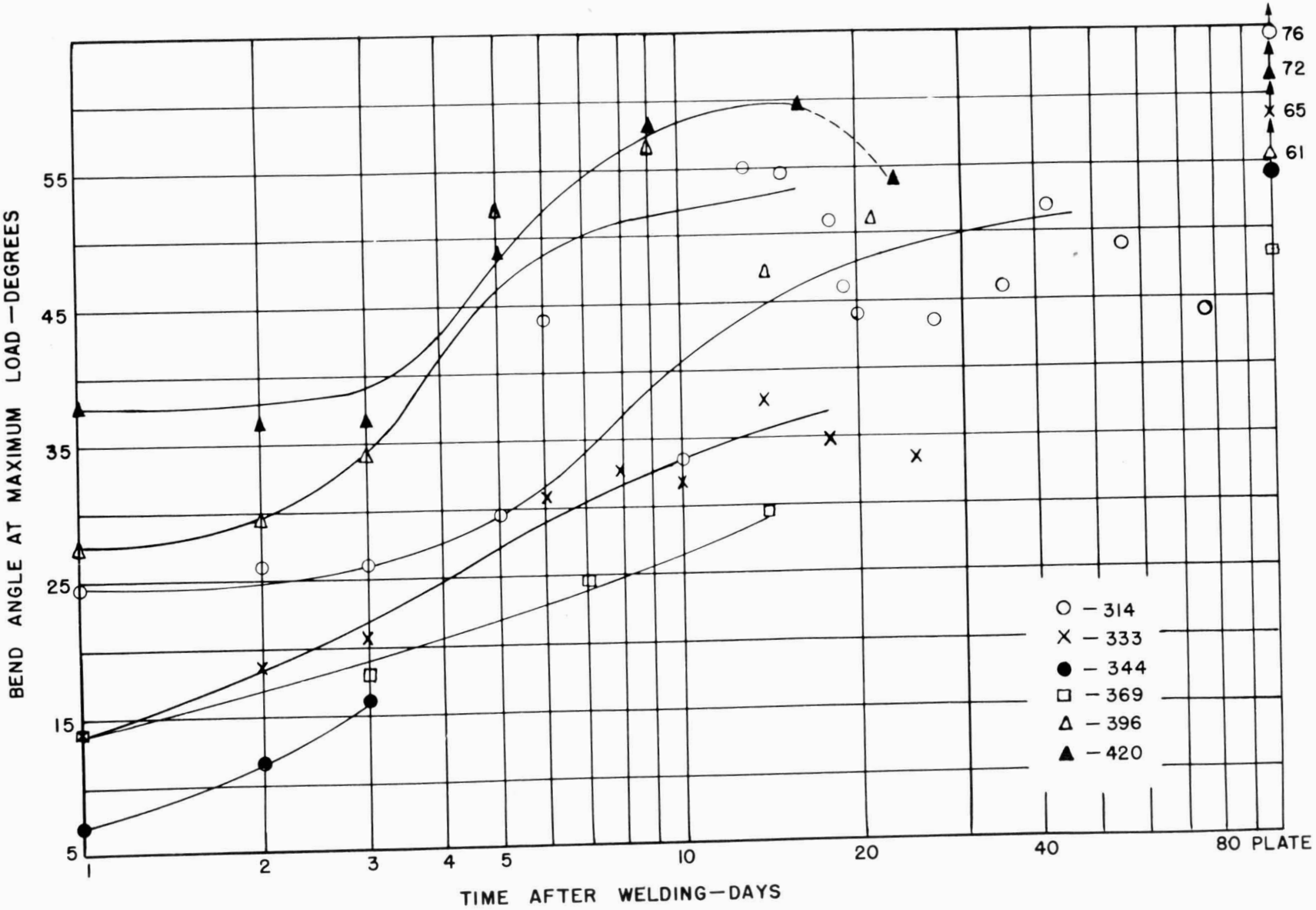

BEND ANGLE AT MAXIMUM LOAD—DEGREES
55
45
35
25
15
5
1
2
3
4
5
10
20
40
80 PLATE
TIME AFTER WELDING—DAYS
76
72
65
61
○ — 314
× — 333
● — 344
□ — 369
△ — 396
▲ — 420

PLATE 9

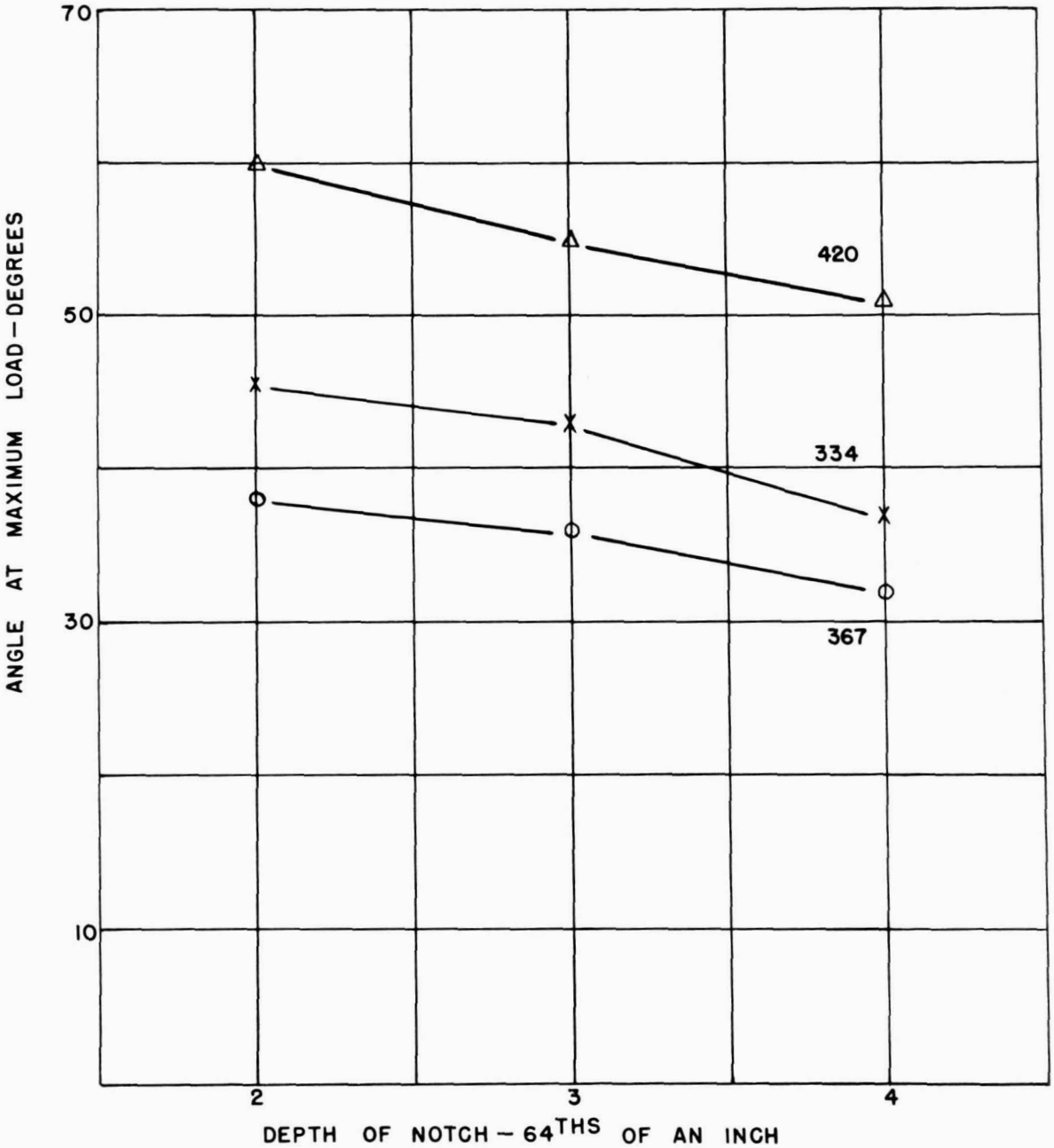

70
50
30
10
ANGLE AT MAXIMUM LOAD—DEGREES
420
334
367
2
3
4
DEPTH OF NOTCH — 64THS OF AN INCH

PLATE 10

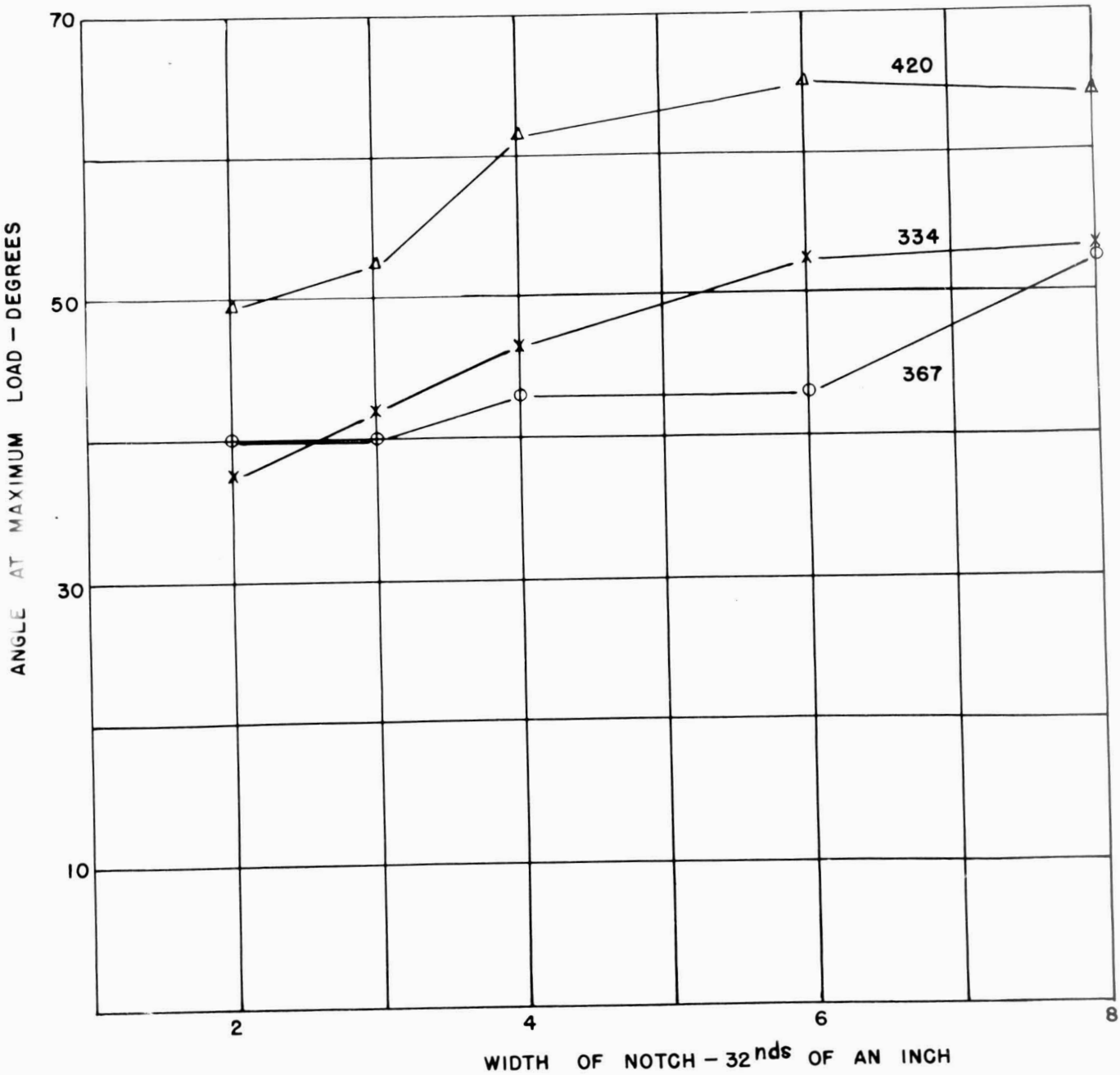

70
50
30
10
ANGLE AT MAXIMUM LOAD – DEGREES
420
334
367
2
4
6
8
WIDTH OF NOTCH – 32nds OF AN INCH

PLATE II

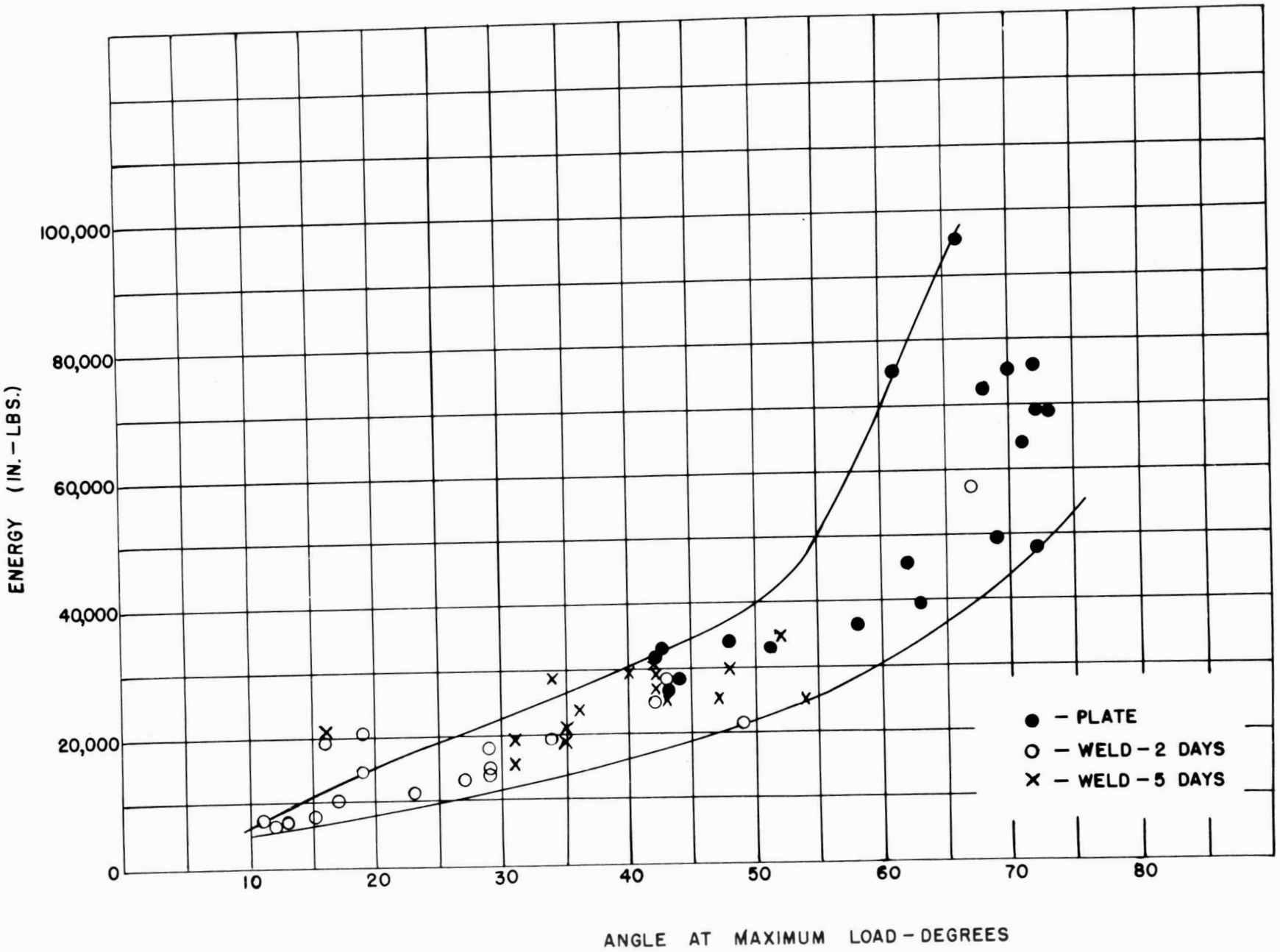

ENERGY (IN.-LBS.)
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
60
70
80
ANGLE AT MAXIMUM LOAD - DEGREES
● - PLATE
○ - WELD - 2 DAYS
× - WELD - 5 DAYS

PLATE 12

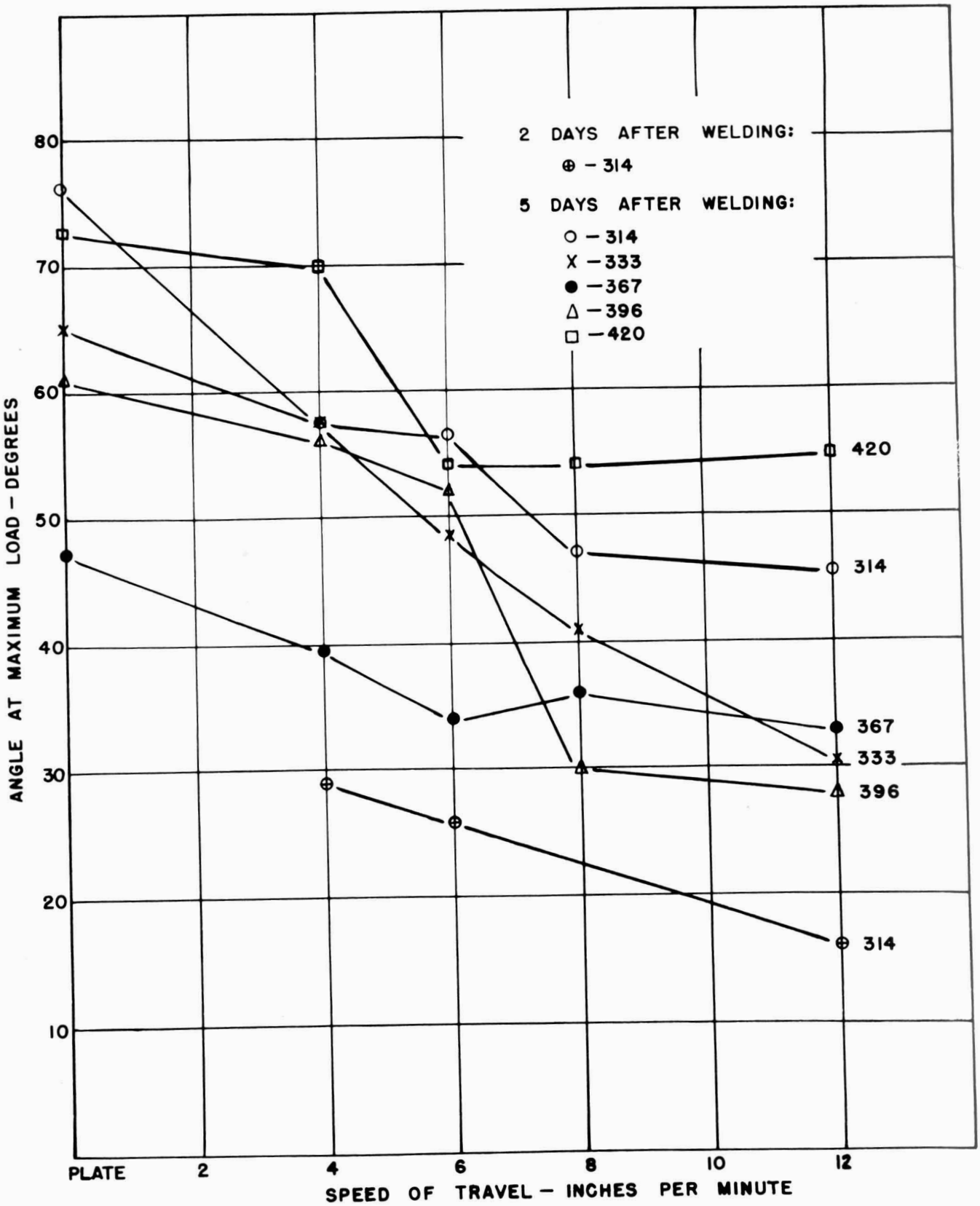
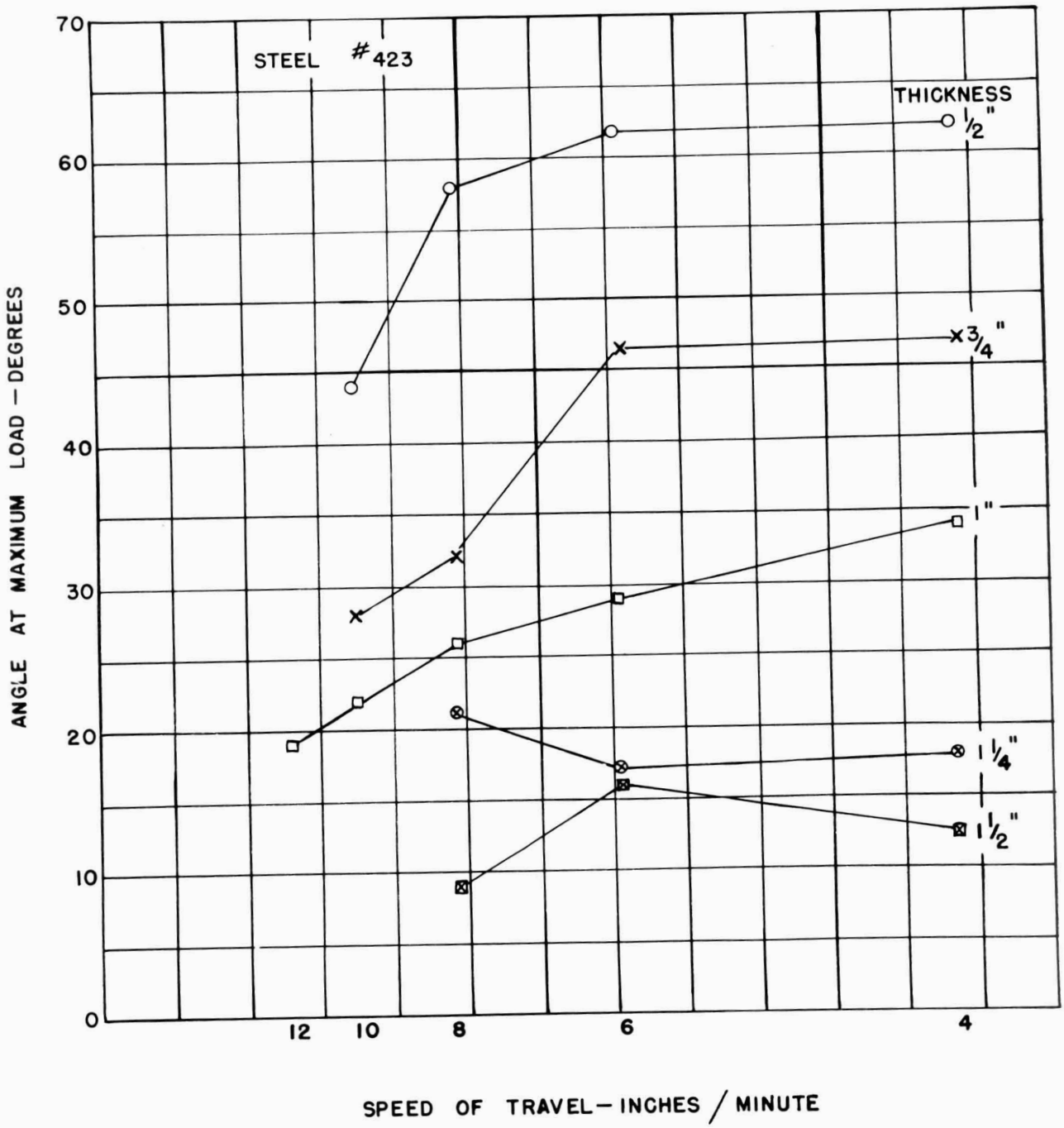

2 DAYS AFTER WELDING:
⊕ – 314
5 DAYS AFTER WELDING:
○ – 314
X – 333
● – 367
△ – 396
□ – 420
80
70
60
50
40
30
20
10
ANGLE AT MAXIMUM LOAD – DEGREES
420
314
367
333
396
314
PLATE
2
4
6
8
10
12
SPEED OF TRAVEL – INCHES PER MINUTE

PLATE 13


STEEL #423
THICKNESS
1/2"
3/4"
1"
1 1/4"
1 1/2"
70
60
50
40
30
20
10
0
12
10
8
6
4
ANGLE AT MAXIMUM LOAD — DEGREES
SPEED OF TRAVEL — INCHES / MINUTE

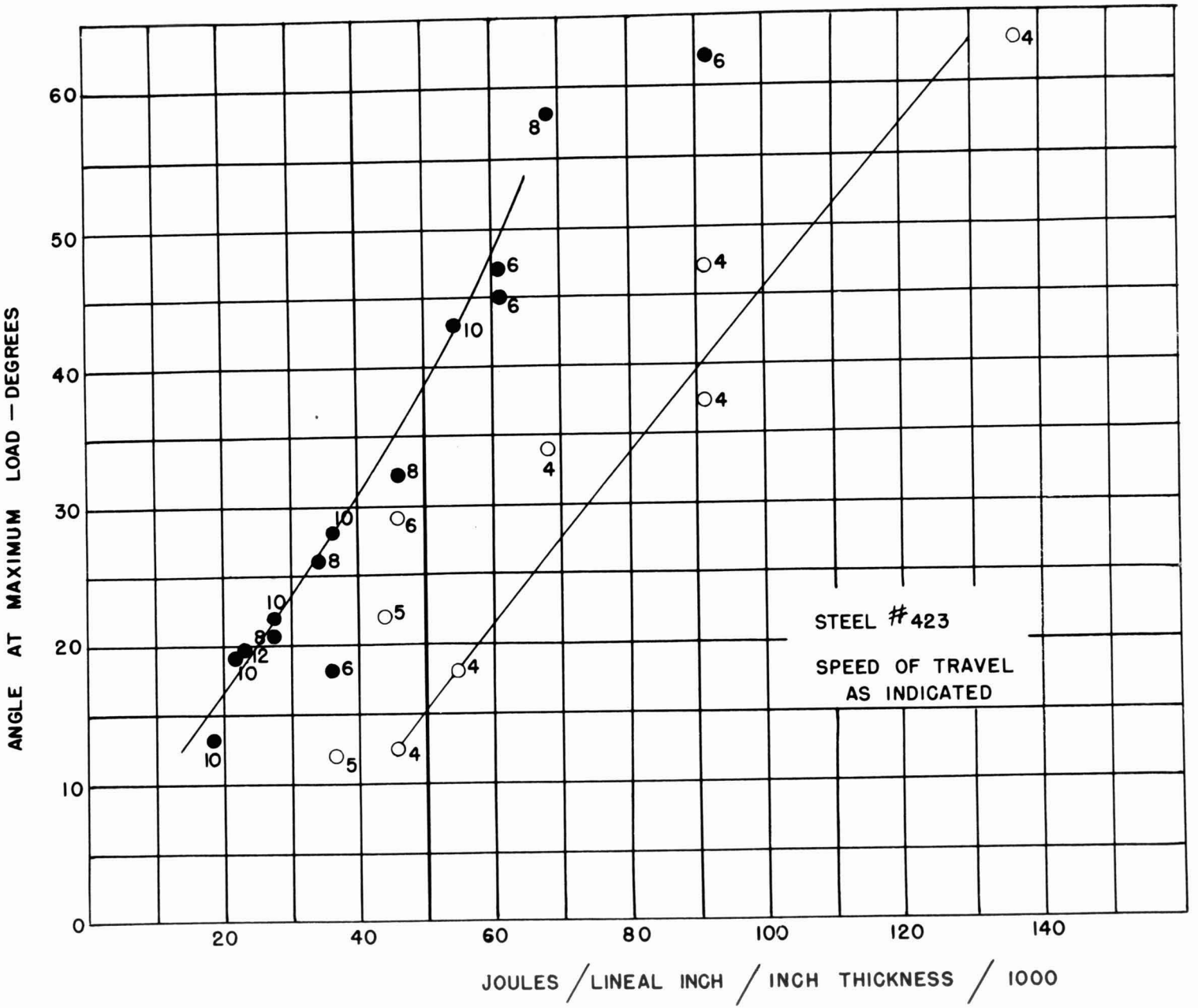

ANGLE AT MAXIMUM LOAD — DEGREES
0
10
20
30
40
50
60
20
40
60
80
100
120
140
JOULES / LINEAL INCH / INCH THICKNESS / 1000
STEEL #423
SPEED OF TRAVEL
AS INDICATED

PLATE 15

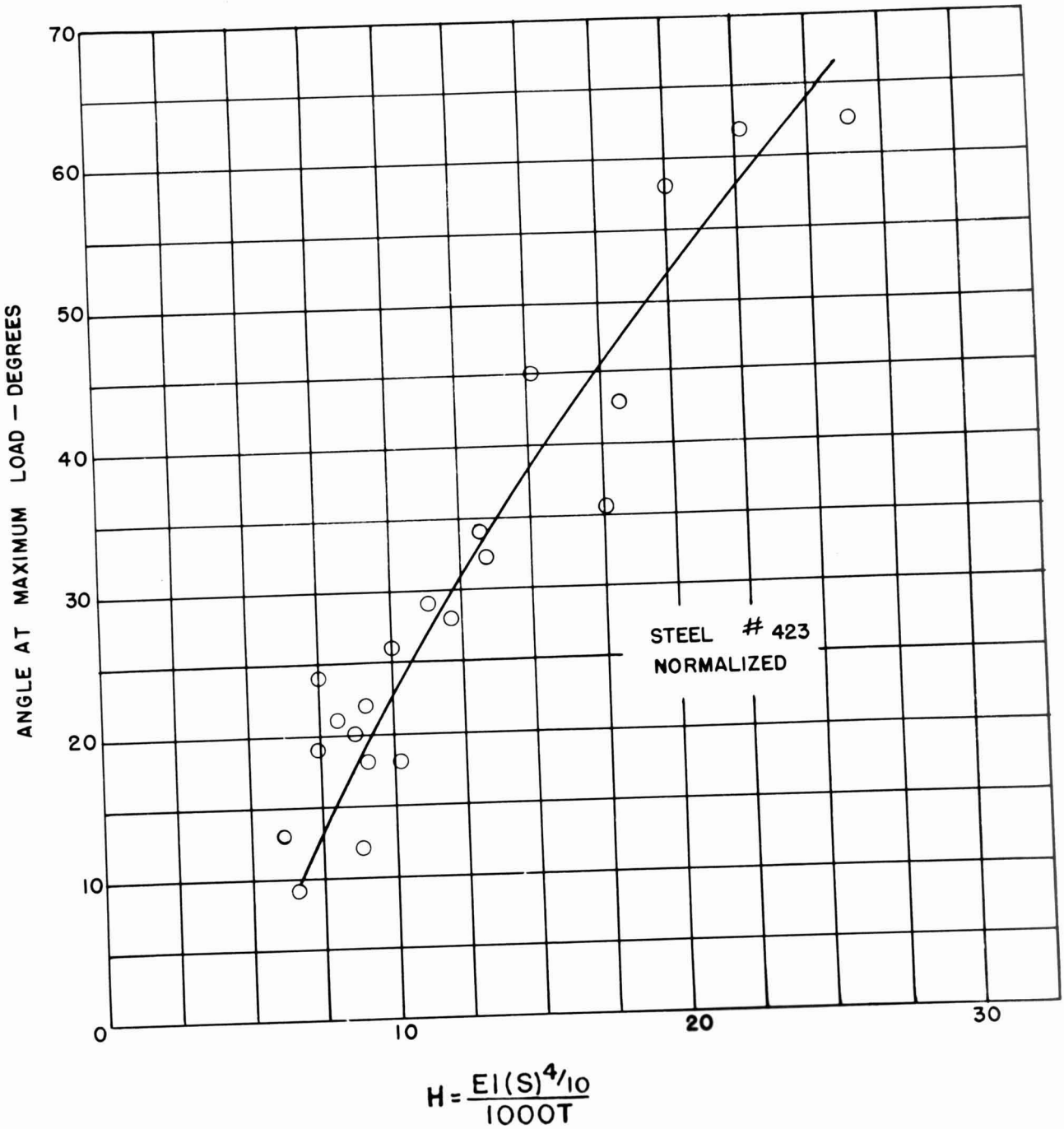
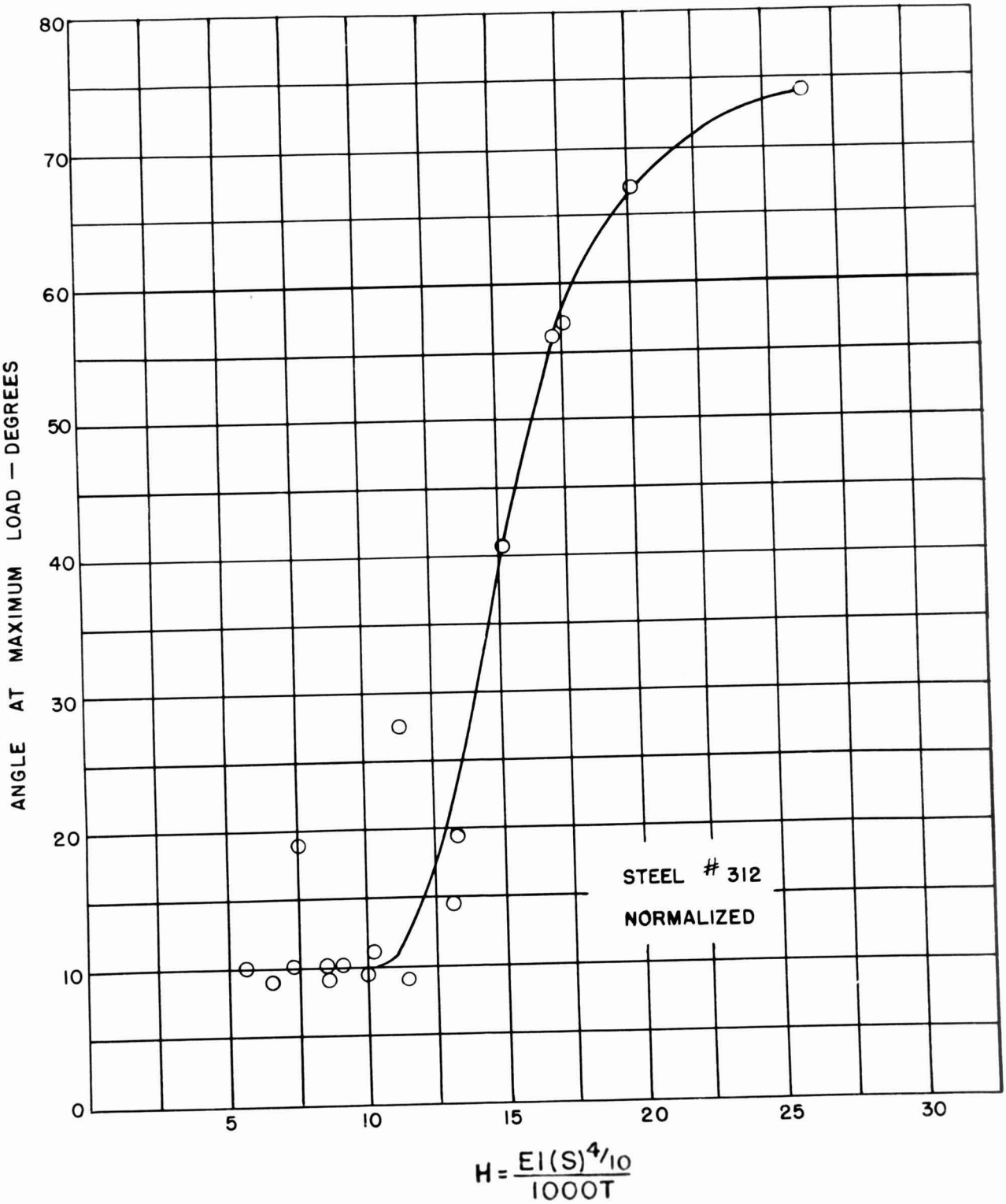

70
60
50
40
30
20
10
0
10
20
30
ANGLE AT MAXIMUM LOAD — DEGREES
STEEL # 423
NORMALIZED
$H = \frac{EI(S)^{4/10}}{1000T}$

PLATE 16


ANGLE AT MAXIMUM LOAD — DEGREES
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
STEEL # 312
NORMALIZED
$H = \frac{EI(S)^{4/10}}{1000T}$

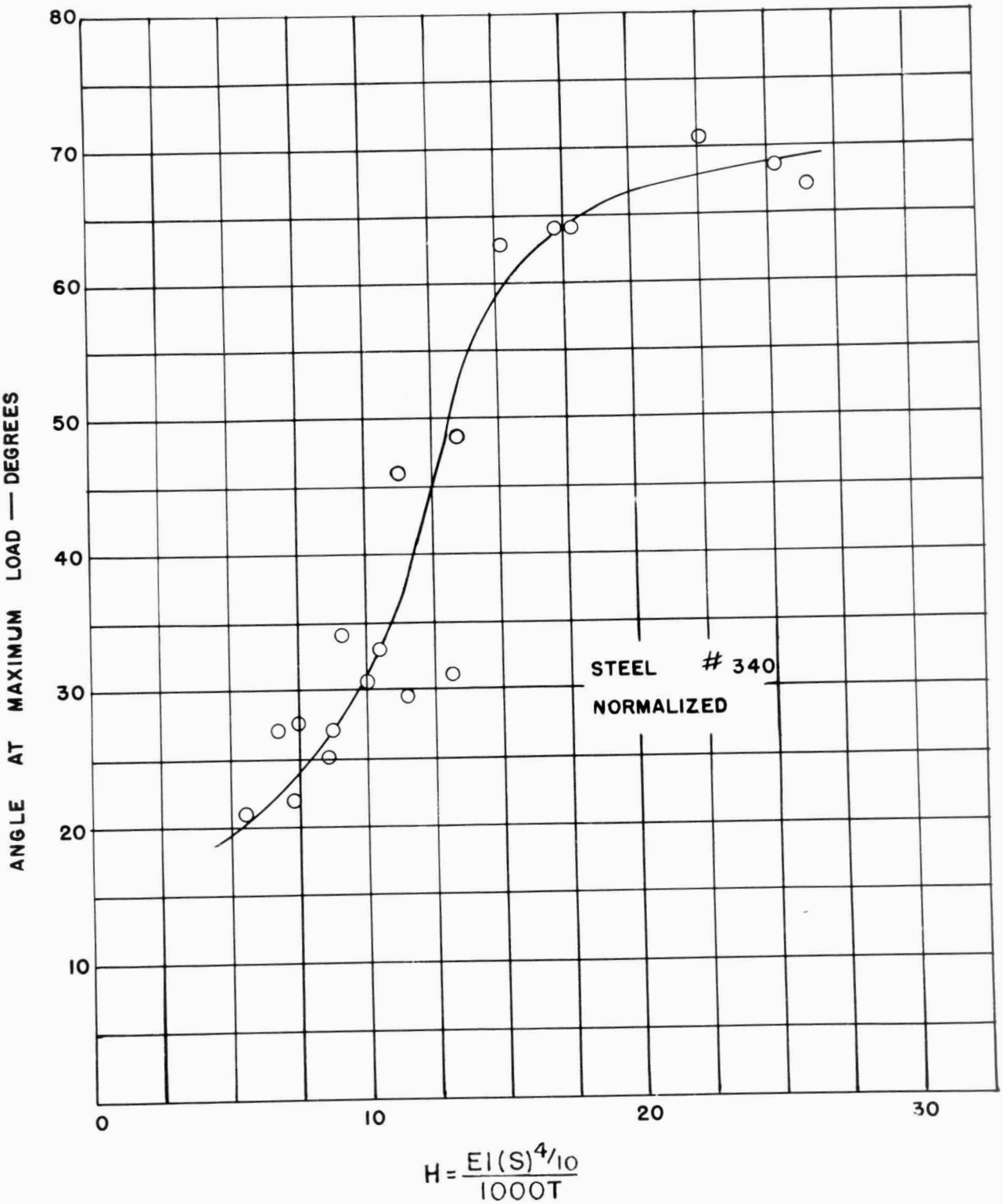

80
70
60
50
40
30
20
10
0
10
20
30
ANGLE AT MAXIMUM LOAD — DEGREES
STEEL # 340
NORMALIZED
$H = \frac{EI(S)^{4/10}}{1000T}$

PLATE 18

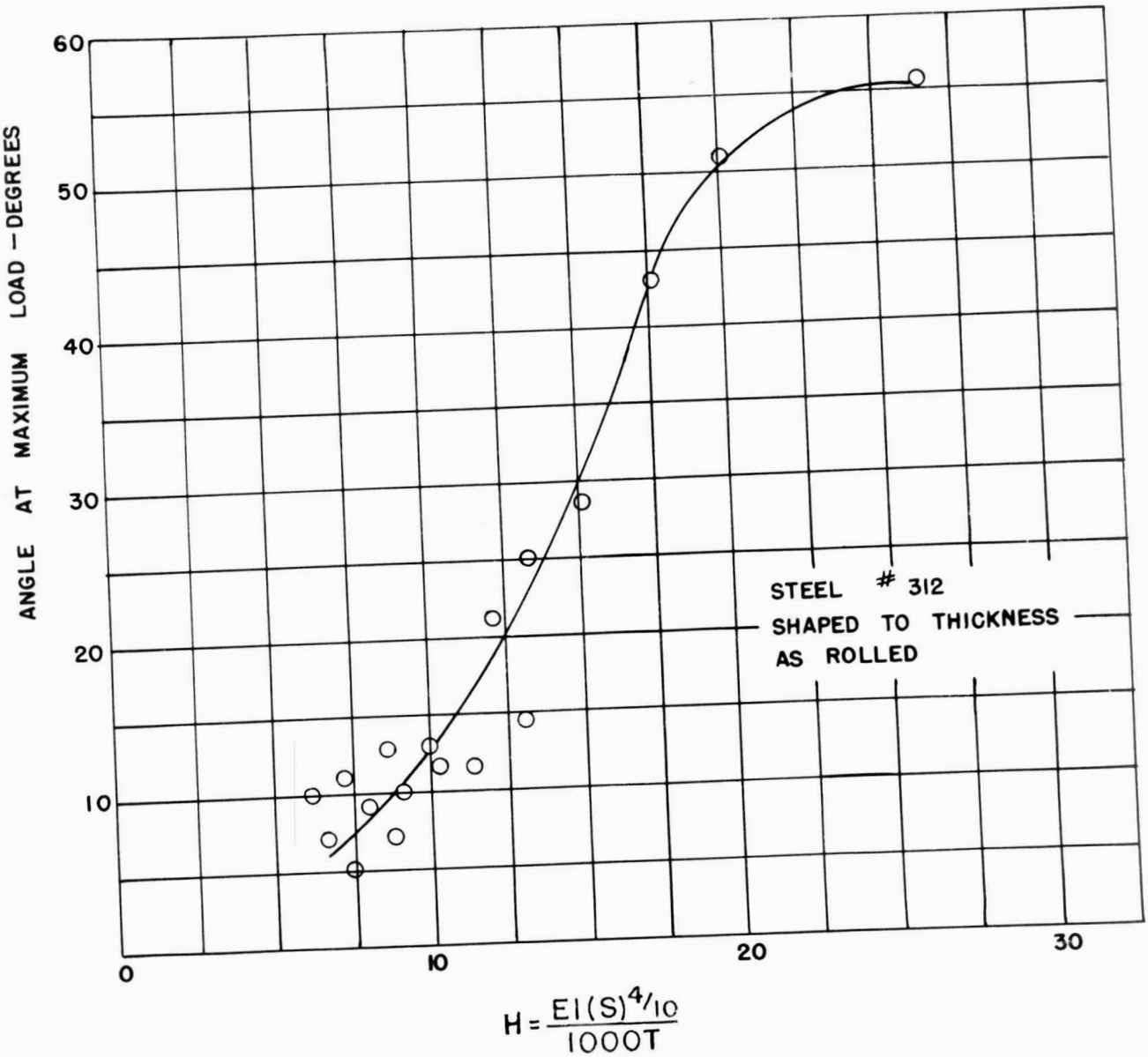

ANGLE AT MAXIMUM LOAD — DEGREES
60
50
40
30
20
10
0
10
20
30
STEEL # 312
SHAPED TO THICKNESS
AS ROLLED
$H = \frac{EI(S)^{4/10}}{1000T}$

PLATE 19

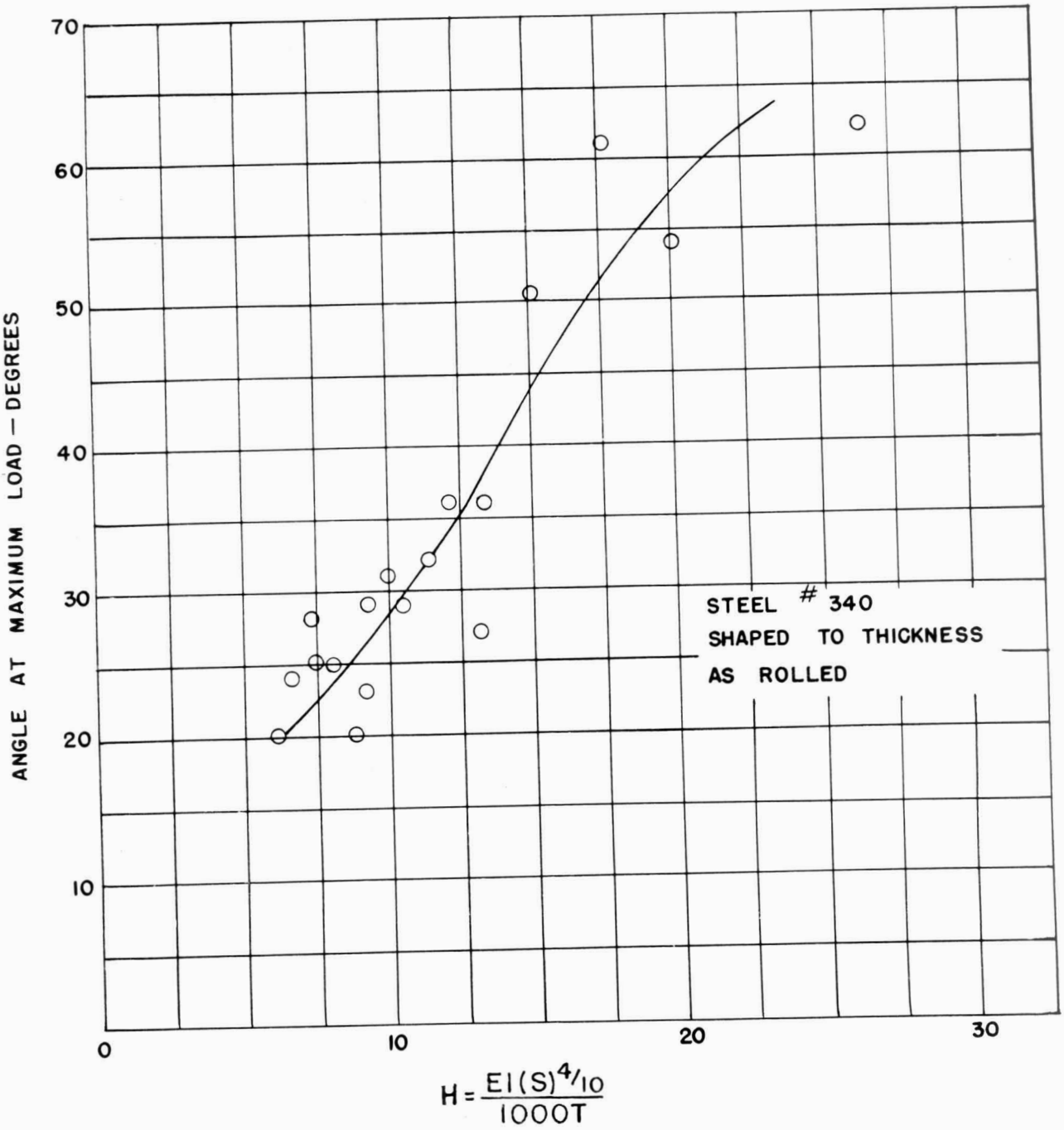

70
60
50
40
30
20
10
0
10
20
30
ANGLE AT MAXIMUM LOAD — DEGREES
STEEL # 340
SHAPED TO THICKNESS
AS ROLLED
$H = \frac{EI(S)^{4/10}}{1000T}$

PLATE 20

APPENDIX 1

Application of Nick-Bend Test

It has been suggested by Jennings (13) that the system reported by Doan, Stout and Frye (8) essentially evaluates the ductility of the heat affected zone by matching the hardness of the ductility specimen and the maximum hardness found in the heat affected zone. It was also suggested that a direct measurement of the ductility in the heat affected zone would eliminate many of the variables encountered in the Lehigh system due especially to the effect of grain size and inaccuracies of the hardness-ductility relation obtained from heat treated specimens. With this in mind the following system is proposed for evaluating the effect of welding on the ductility of a steel. It is recognized that the system suggested here is basically a simplification of the Lehigh system. The steps in this proposal are:

1. Determine the relationship of ductility and effective welding power input by use of the nick-bend test.

2. Determine from the relationship of step (1) the power requirement per inch of thickness for a ductility of 25° or other desired value.

3. Determine from the configuration of the joint the equivalent thickness of the joint.

4. Maintain the power level from step (2) for all welding or adjust with preheat when power input per inch of thickness becomes low.

The concept of equivalent thickness of a joint requires only a brief comment. If the metal in a joint were distributed uniformly in a plate, that plate would have a certain thickness depending upon the configuration of the joint. In other words the last pass for a single V groove weld would have an equivalent thickness of one inch, while the first pass would have an equivalent thickness of slightly less than one inch. In Fig. 21 (a), it can be readily seen that if the metal were rearranged to form a single plate, that it would have a thickness of $1\frac{1}{4}$". This concept is simple enough so that most joints may be evaluated and it is useful in analyzing the effective volume of metal contiguous to a weld. Usually the accuracy required does not necessitate a detailed measurement of the areas in the joint. The equation $H = \frac{EI(S)^{4/10}}{T}$ may be used for calculating the relation of the various quantities desired in any given problem. The use of a nomographic chart of the relation between effective power input, welding current, arc length and speed of travel is, however, more convenient; such a chart is shown in Fig. 22. Any straight line across the scales will give the effective power input for a speed of travel of 6" per minute for the indicated arc current and voltage. For example, with a minimum power requirement of 16,250 units, 6" per minute travel and a 28 volt arc length the required welding current will be 230 amperes. If information is desired for other speeds of travel than 6 inches per minute the effective power input must be converted to the desired speed of travel. For example, an effective power input of 20,000 units at 6" per minute will be reduced to 16,000 units by increasing the speed to 10" per minute.

A number of examples will aid in more clearly illustrating the method of attack proposed.

PROBLEM 1

Let us assume that we are interested in welding a T-joint with a fillet joining a 1/2 inch plate to a plate 1 inch in thickness (Fig. 21(a)) (Table 2), of normalized steel #312. It is desired to determine the minimum power level to insure 25° bend ductility.

Step 1 - The relationship of ductility and welding power input was determined by use of the nick-bend test (Fig. 17) Steel #312.

Step 2 - A power level of 13,000 units per inch thickness will be required (Fig. 17).

Step 3 - The equivalent plate thickness is $1\frac{1}{4}$ inches.

Step 4 - The minimum power level will be $1\frac{1}{4}$ x 13,000 or 16,250 units.

From Figure 22 at 6" per minute travel and a 28 volt arc length, 230 amperes should be the minimum power level. The use of a $\frac{1}{4}$" diameter electrode is indicated.

PROBLEM 2

Let us assume that it is desired to add a 1 inch thick plate to the joint in Problem 1 opposite the $\frac{1}{2}$ inch plate making a cruciform joint (Plate 21(b)). The requirement of 25° ductility is to be met.

Step 1 - Same as step 1, problem 1.

Step 2 - Same as step 2, problem 1.

Step 3 - The equivalent plate thickness has been increased to 1-3/4 inches.

Step 4 - The minimum power level will be 1-3/4 x 13,000 or 22,750 units.

From Figure 22 at 6 inches per minute speed of travel and a 30 volt arc length, 310 amperes should be the minimum power level. The use of a 1/4" diameter electrode is indicated. If a lower power level is desired the use of preheat will be necessary.

PROBLEM 3

Let us assume that we wish to weld a $\frac{1}{4}$ inch thick gusset to a $\frac{1}{2}$ inch thick flange (Fig. 21(c)), using normalized Steel #340, maintaining a ductility of 25°.

Step 1 - The relationship of ductility and welding power input was established by use of the nick-bend test (Fig. 18 for Steel #340).

Step 2 - A power input of 9,000 units per equivalent inch in thickness will be required (Fig. 18).

Step 3 - The equivalent plate thickness is 5/8 inches.

Step 4 - The minimum power level will be 5/8 x 9,000 units or 5,625 units.

From Figure 22 a power requirement of 5,625 units at 10 inches per minute speed of travel is equivalent to 7,100 units at 6" per minute. With a 28 volt arc length, 100 amperes should be the minimum power level. The use of a 1/8" diameter electrode is indicated.

PROBLEM 4

Let us assume that we wish to weld a corner joint between a ½" plate and a 1" plate (Fig. 21 (d)), using normalized steel #423 (Table 2). It is desired to establish a safe welding technique in order to maintain a ductility of 35°.

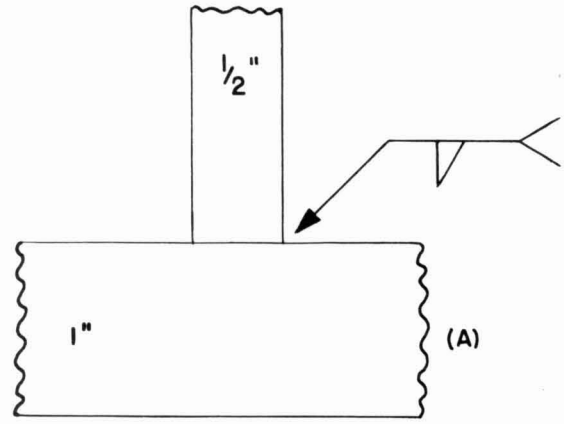
Step 1 - The relationship of ductility and welding power input was established by use of the nick-bend test (Fig. 16) for Steel #423.

Step 2 - A power input of 13,000 units per inch thickness will be required (Fig. 16).

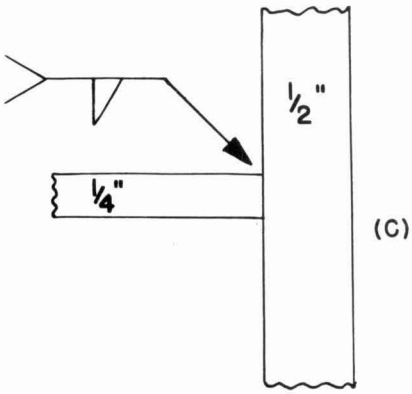
Step 3 - The equivalent plate thickness is 3/4 inch.

Step 4 - The minimum power level will be 3/4 x 13,000 or 9,750 units.

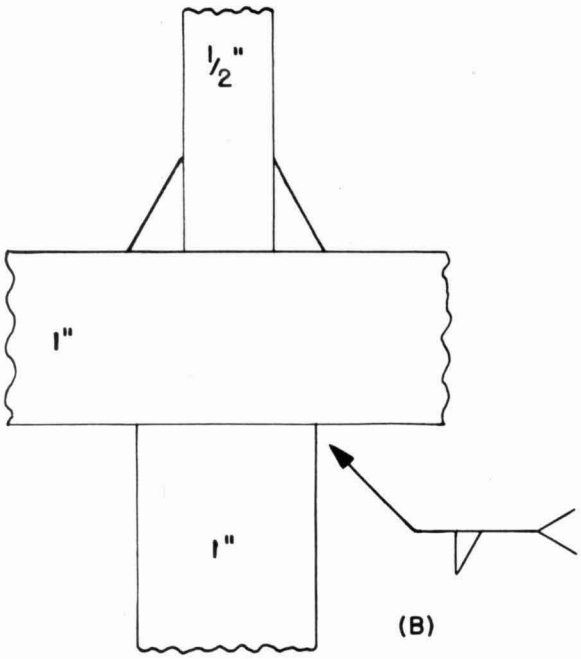
From Figure 22 at a speed of travel of 6" per minute and 28 volts arc length, 140 amperes will be required. The use of a 5/32" diameter electrode is indicated.



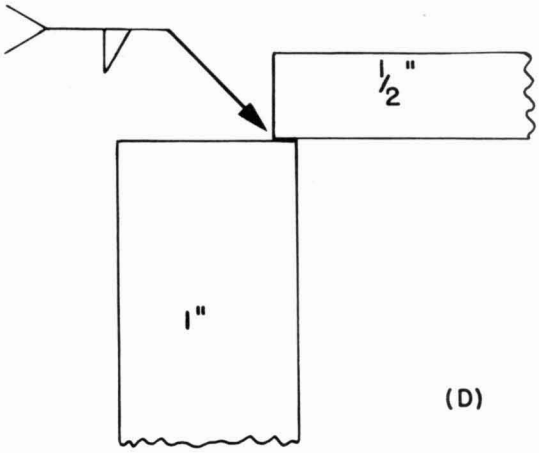
STEEL #312



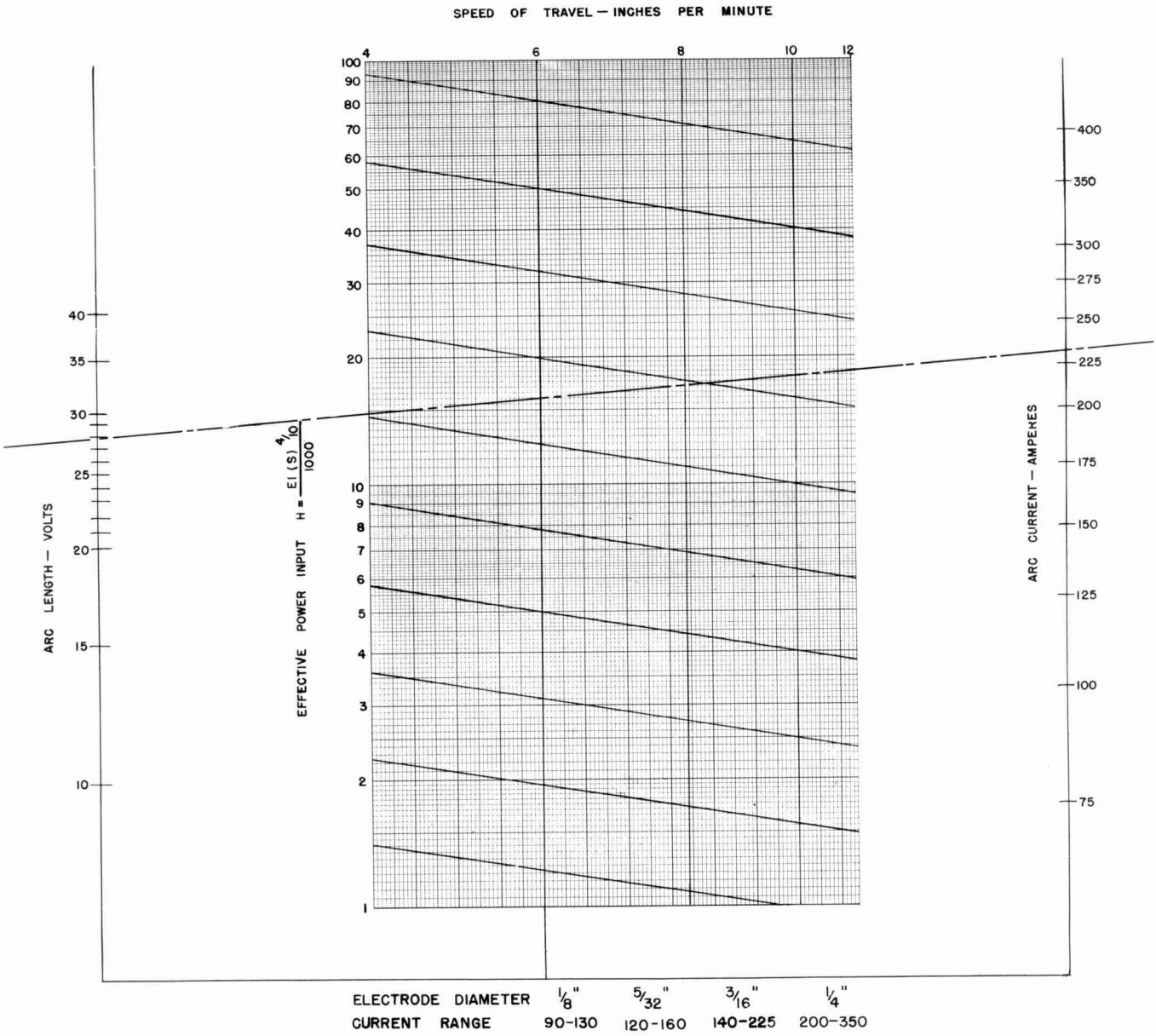
STEEL #340



STEEL #312



STEEL #423



RELATION OF EFFECTIVE POWER INPUT WELDING CURRENT, ARC LENGTH AND SPEED OF TRAVEL.