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The Effect of Fabrication Processes on Steels Used in Pressure Vessels

by

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Pressure Vessel Research Committee

Welding Research Council

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Introduction

The effect of fabrication processes on steels used in pressure vessels is a subject to which considerable attention has been devoted by the Fabrication Division of the Pressure Vessel Research Committee of the Welding Research Council. It is desired to know which fabrication operations are harmful to the mechanical properties of steels, and to what extent. Eventually this information should lead to materials specifications and to codes of recommended fabrication practice, based on measured responses of steel to various treatments. With these objectives, the Pressure Vessel Research Committee is sponsoring a project at Lehigh University.

In earlier investigations[1,2,3] the effect of various simulated fabrication operations was determined by measuring the changes in transition temperature, strength and ductility of the material. These fabrication processes included various degrees of plastic prestrain produced by uniaxial stress, and various post heat treatments.[3]

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1, 2, 3. These numbers refer to references at the end of this report.

This report considers another fabrication process-welding. It was desired to know how different grades of pressure vessel steels respond to welding, and to observe the effects of plate thickness, of high and low heat input during welding, of plastic strains before welding, and of heat treatments after welding.

Materials

For the tests reported here, six plain carbon steels were selected from several mills to cover a range of grades, carbon contents and deoxidation practices. A complete history is available[2] for two of the steels used, each in two thicknesses, Steels A and E of 5/8" thickness, and Steels B and F of 1 1/4" thickness. These steels were made especially for research purposes. The others were ordered from regular mill stock. Samples for chemical analysis were taken from the steels according to recommended A.S.T.M. procedure and the results of these analyses are given in Table I. Also included in Table I are strength and ductility data for the as-rolled plate as determined by standard 0.505" tensile tests at Lehigh University.

Specimen Preparation and Testing

The transition temperature of each steel was determined for each of the following conditions:

A. Welded

B. Welded and heat treated at 500°F

C. Welded and heat treated at 1150°F

D. Elongated 5% and welded

E. Elongated 5%, welded and heat treated at 500°F

F. Elongated 5%, welded and heat treated at 1150°F

This schedule was followed for two heat inputs - 175 amperes at 10 inches per minute with an E6010 3/16" electrode (called W1), and 275 amperes at 8 inches per minute with an E6010 1/4" electrode (called W2). To cut down on expensive machining operations, conditions B and E were not used for the 1 1/4" plate (Steels B and F).

The longitudinal bead notch-bend test, Fig. 1, was used as developed by a Welding Research Council project at Lehigh University.[4] With an automatic welding machine, a weld bead ten inches long was deposited on a plate surface of the 3"x12" specimen. Heat treating was done one day after welding. The 5/8" plate was then notched and tested at plate thickness, while the 1 1/4" plate was shaped down on the unwelded surface to a thickness of 5/8" before notching. Specimens were tested one week after welding.

The 5% prestrain for sections D, E and F above, was produced by stretching strips 9 1/2" by 16' in an 800,000 pound testing machine. Gage marks were scribed at two-foot intervals along the strips and the distances between ~~each was~~ marks were ~~checked~~ measured regularly during the pulling. A two-foot section from each end of ~~the~~ each strip~~s~~ was discarded to avoid using material which had been non-uniformly deformed because of the restraints at and near the testing machine grips.

The specimens were tested in bending, as in Fig. 2. Three measurements were made on each specimen - percent lateral contraction, percent of the fracture area which was cleavage, and energy absorbed by the specimen from the start of the test until the load had passed its maximum and dropped to a value equal to half the maximum. The percent contraction values were obtained by measuring with a pointed micrometer the width of the specimen 1/32 inch below the notch before and after the test. Percent cleavage measurements were made on a fractured section with a steel scale. Energy values were determined by measuring with a planimeter the area under a load-deflection curve obtained autographically during the test.

Twelve specimens, or twenty-four notch tests, were used for each condition, four tests at each of six temperatures. The average values at each temperature were connected by straight lines, and the transition temperature was the point at which the percent contraction, percent cleavage or energy was equal to half its maximum. When occasionally the transition curve formed a plateau near the transition temperature, a transition range was reported as well as a transition temperature. This range extended from the temperature of -10% to that of +10% of the half-maximum value of contraction, cleavage or energy which had defined the transition temperature. T_N and T_E, the transition temperatures obtained from percent contraction and energy curves, respectively, were considered the transition temperatures of the material with the original notch. T_B, obtained from percent cleavage curves, was considered the transition temperature of the plate when notched by a crack. All three temperatures are listed in Tables II, III and IV.

T_E, as described here, is a transition temperature not previously determined or reported in the earlier papers. T_E was found to agree very closely with T_N for unstrained material, and to be consistently lower than T_N for strained material. Fig. 3 shows typical energy and contraction curves for strained and unstrained material.

To determine the effects of welding, the transition temperatures of welded specimens were compared with those of unwelded specimens from the same material. Although transition curves for the as-received condition had been made earlier for steels B and F[1,3], they were repeated for use in the present work. It was found that there were some differences between the two sets of curves, which are shown in Fig. 4 to 7. The discrepancies between the curves must be accounted for by variation from plate to plate[2], and by inaccuracy caused by the method of plotting. From these curves, it appears that variations in transition temperature as high as 30°F could be intrinsic to plate variations and to the testing and plotting methods, and could not be attributed with surety to the variable being studied.

Discussion of Results

Effect of Welding As-Rolled Plate

Welding increased notch-sensitivity of as-received plate when measured by % contraction or energy. The difference between unwelded and welded plate was shown by a significant rise in the transition temperatures T_N and T_E, both of which are affected by the material directly below the machined notch.

The rise in T_N caused by welding as-received plate is shown graphically in Fig. 8. The order of transition temperatures after welding was quite different from that before welding.

The notch-sensitivity measured by fracture appearance was little affected by welding. This is shown in Fig. 9 by a small rise, or even a drop, in T_B values from unwelded to welded plate.

Effect of Welding Prestrained Plate

As seen in Fig. 10, prestraining often but not always raised somewhat the transition temperatures of as-received plate. The effect of welding this plastically prestrained plate is shown in Figs. 11 and 12. As in the case of as-rolled plate, the T_N for strained plate was significantly raised by welding (Fig. 11). The T_N level after welding strained metal was a little higher than that after welding unstrained metal (Fig. 13).

When the effect of welding prestrained steel is considered in the light of the transition temperature T_B, in Fig. 12, it can be seen that T_B for strained steel was raised up to 75°F by welding. T_B for strained and welded plate was, in most cases, appreciably higher than that for unstrained and welded plate (Fig. 14).

Effect of Heat Input

In comparing the differences in level between W1 and W2 in Figs. 8, 9, 11 and 12, it may be noted that, except in two cases, the two heat inputs resulted in about the same transition temperature for these plain carbon steels.

Effect of Plate Thickness

It can be seen from Figs. 8 to 11 that welding usually caused greater increases in T_N for Steels E and F, which were welded at 1 1/4" thickness, than it did for the other steels, welded at 5/8" thickness. Since all the steels were tested in 5/8" thickness, this indicates that the increased cooling rate after welding imposed by the thicker plate resulted in a higher T_N transition temperature. The T_B transition temperature, Figs. 9 and 12, was changed by welding to about the same degree for 1 1/4" and 5/8" plate.

Effect of Carbon Content and Deoxidation Practice

There appeared to be some correlation between carbon content and transition temperatures, both before and after welding, as shown in Fig. 15. This figure contains only the values for the steels of 5/8" thickness.

In Fig. 16 the steels are grouped according to deoxidation practice. According to either T_N or T_B, the rimmed steels had the highest transition temperatures after welding, the killed steel with aluminum addition next, followed by the semi-killed and straight silicon-killed steels. It is interesting to note that the four steels selected at random from mill stock compared favorably with the two pedigreed steels prepared especially for research purposes.

Effect of Heat Treatment after Welding

The effect of a 500°F heat treatment after welding unstrained metal at the lower heat input is illustrated in Fig. 17. The heat treatment has little effect - it sometimes lowered T_N and T_B slightly and sometimes raised them. The

1150°F postheat, however (Fig. 18), lowered T_N by as much as 70 degrees, while T_B was unaffected.

Strained and welded metal, however, responded more readily to heat treatment. In Fig. 19 it can be seen that even the 500° postheat lowered T_N somewhat; ~~while~~ it left T_B unchanged. The 1150° postheat, as shown in Fig. 20, resulted in a lowering of T_N by as much as 100°, and also a consistent lowering of T_B.

The same responses were found after the higher heat input weld.

Effect of Welding on Hardness

A study was made of the hardness of the material immediately below the weld in all conditions. It revealed little beyond the fact that welding increased the hardness in this area, and that the 1150° postheat had a very slight softening effect.

Summary

1. Welding appreciably increased the notch-sensitivity of the material ~~near the weld~~. The increase could not be predicted from the transition temperature of the unwelded plate.

2. Welding prestrained material resulted in a T_N and T_B of slightly higher level than welding unstrained plate.

3. Welding raised the T_N transition temperature of thick plate more than thin plate.

4. The level of transition temperature was apparently a function of carbon content and deoxidation practice.

5. An 1150°F heat-treatment after welding greatly improved the material affected by the weld. A 500°F post heat improved strained and welded material, but not unstrained welded material.

Acknowledgments

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The project was carried on jointly by the Fritz Engineering Laboratory of the Civil Engineering Department, and the Metallurgy Department of Lehigh University. The execution of work was made possible by the cooperation of Kenneth R. Harpel, laboratory foreman, and the entire laboratory staff.

References

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3. Osborn, C.J., Scotchbrook, A.F., Stout, R.D., and Johnston, B.G., "Effect of Plastic Strain and Heat Treatment", The

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4. Stout, R.D., McGeady, L.J., Sun, C.P., Libsch, J.F., and Doan, G.E., "Effect of Welding on Ductility and Notch Sensitivity of Some Ship Steels", The Welding Journal, 26(6), Research Suppl., 335-s to 357-s (1947).

Table I

Project Letter	A.S.T.M. No.	Deoxidation	Plate Thickness	C	Mn	P	S	Si	Al	Al_2O_3	N_2	Lower Yield Strength p.s.i.	Maximum Strength p.s.i.	% Red. of Area	% Elongation
I	A-285 Grade A	Rimmed	5/8"	.15	.38	.012	.030	.01	.010	.007	.004	34,650	59,150	63.8	38.0
K	A-285 Grade A	Semi-killed	5/8"	.09	.43	.014	.027	.02	.011	.005	.004	29,600	51,450	73.5	42.3
L	A-285 Grade C	Rimmed	5/8"	.20	.40	.011	.030	.01	.008	.006	.003	32,050	61,400	56.3	37.5
E	A-70 Grade C	Rimmed	5/8"	.22	.37	.019	.028	.02	.010	.002	.004	33,850	64,200	63.2	38.5
F	A-70 Grade C	Rimmed	1 1/4"	.20	.35	.018	.028	.02	.021	.003	.003	26,250	56,300	63.1	39.5
A	A-201 Grade A	Killed	5/8"	.17	.55	.020	.022	.21	.041	.003	.005	35,450	63,150	68.6	38.0
B	A-201 Grade A	Killed	1 1/4"	.15	.55	.020	.019	.20	.041	.006	.004	31,600	63,300	64.6	36.8
P	A-201 Grade A	Killed	5/8"	.12	.41	.015	.027	.19	.018	.007	.003	32,850	57,350	66.7	38.9

TABLE II - EFFECT OF WELDING ON TRANSITION TEMPERATURE

CRITERION - T_N

Steel	As Rolled	welded W_1° unstrained	welded W_2°° unstrained	welded W_1 post heat 500°F	welded W_2 post heat 500°F	welded W_1 post heat 1150°F	welded W_2 post heat 1150°F	strained 5% unwelded	strained 5% welded W_1	strained 5% welded W_2	strained welded W_1 post heat 500°F	strained welded W_2 post heat 500°F	strained welded W_1 post heat 1150°F	strained welded W_2 post heat 1150°F
A	-35	33	-18	15	- 8	-30	3	-45	35	20	3	20	-18	6
B	-85	43	47	-	-	7	19	-35	89	93	-	-	-15	0
P	-73	18	30	27[a]	-11	-55	-24	-75	77[b]	11	0	31[c]	-20[d]	-24
I	-28	28	66	41	28	-18	35	-53	45	26	40[e]	15	- 5	-11
K	-53	12	-17	8	-30	-40	-25	10	71	40	53	27	-18	-23
L	-51	63	58	79	59	35	56	- 7	92	88	45	83	-10	48
E	-13	75	68	68	63	30	50	8	80	58	58	40	-13	38
F	-71	81	66	-	-	17	21	48	150	62	-	-	88	18

° W_1 - Welded using 175 amperes at 10 inches per minute with an E6010 3/16" electrode.
°° W_2 - Welded using 275 amperes at 8 inches per minute with an E6010 1/4" electrode.
a - Temperature Range -5 to 32
b - Temperature Range 45 to 82
c - Temperature Range 0 to 43
d - Temperature Range -26 to 32
e - Temperature Range 0 to 50

TABLE III - EFFECT OF WELDING ON TRANSITION TEMPERATURE

CRITERION - T_E

Steel	As Rolled	welded w_1° unstrained	welded w_2°° unstrained	welded w_1 post heat 500°F	welded w_2 post heat 500°F	welded w_1 post heat 1150°F	welded w_2 post heat 1150°F	strained 5% unwelded	strained 5% welded w_1	strained 5% welded w_2	strained welded w_1 post heat 500°F	strained welded w_2 post heat 500°F	strained welded w_1 post heat 1150°F	strained welded w_2 post heat 1150°F
A	-36	29	-34	-11	-16	-80	- 3	-59	7	- 5	-18	-18	-59	- 8
B	-96	45	55	-	-	-18	5	-58	90	88	-	-	-24	-25
F	-74	17	22	20	-35	-41	-23	-67	49	-18	-28	-36	-41	-46
I	-33	29	61	27	5	-68	-15	-84	0	- 2	-18	-13	-13	-33
K	-54	11	-27	2	-31	-50	-21	-39	46	18	33	15	-28	-29
L	-58	52	51	75	40	13	53	-20	26	38	-26	18[a]	-25	25
E	-13	65	50	33	2	-52[b]	30	-13	14	13	3	8	-21	12
W	-75	100	69	-	-	7	33	-11	136	3	-	-	30	22

° W_1 - Welded using 175 amperes at 10 inches per minute with an E6010 3/16" electrode.

°° W_2 - Welded using 275 amperes at 8 inches per minute with an E6010 1/4" electrode.

a - Temperature Range - 3 to 60

b - Temperature Range -58 to 15

TABLE IV - EFFECT OF WELDING ON TRANSITION TEMPERATURE

CRITERION - T_B

Steel	As Rolled	welded W_1° unstrained	welded W_2°° unstrained	welded W_1 post heat 500°F	welded W_2 post heat 500°F	welded W_1 post heat 1150°F	welded W_2 post heat 1150°F	strained 5 % unwelded	strained 5 % welded W_1	strained 5 % welded W_2	strained welded W_1 post heat 500°F	strained welded W_2 post heat 500°F	strained welded W_1 post heat 1150°F	strained welded W_2 post heat 1150°F
A	65	68	53	35	53	45	25	50	90	108	115	111	84	68
B	81	78	70	-	-	67	64	83	95	118	-	-	91	94
P	-50	13	30	13	-11	28	-16	-10	57	65	56	44	48	38
I	45	80	75	83	74	84	61	79	114	85	113	86	88	57
K	55	66	47	55	38	60	75	79	117	97	103	86	80	61
L	87	97	93	92	108	110	100	108	156	148	153	142	131	107
E	110	95	98	109	119	133	113	118	153	150	175	127	125	115
F	180	157	158	-	-	156	164	163	163	212	-	-	158	166

° W_1 - Welded using 175 amperes at 10 inches per minute with an E6010 3/16" electrode.

°° W_2 - Welded using 275 amperes at 8 inches per minute with an E6010 1/4" electrode.

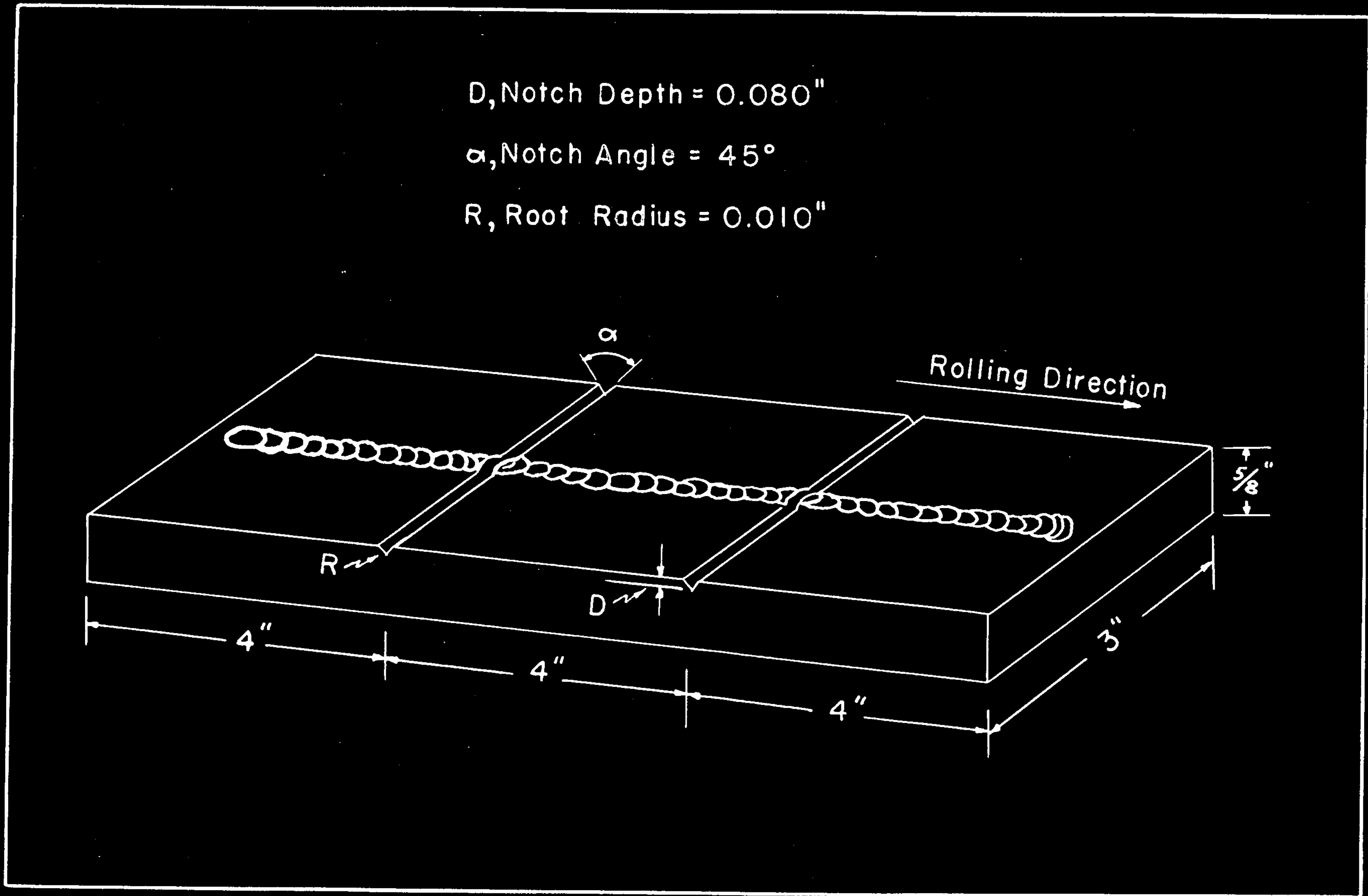


Fig.1 LEHIGH SLOW NOTCHED BEND SPECIMEN WITH WELD

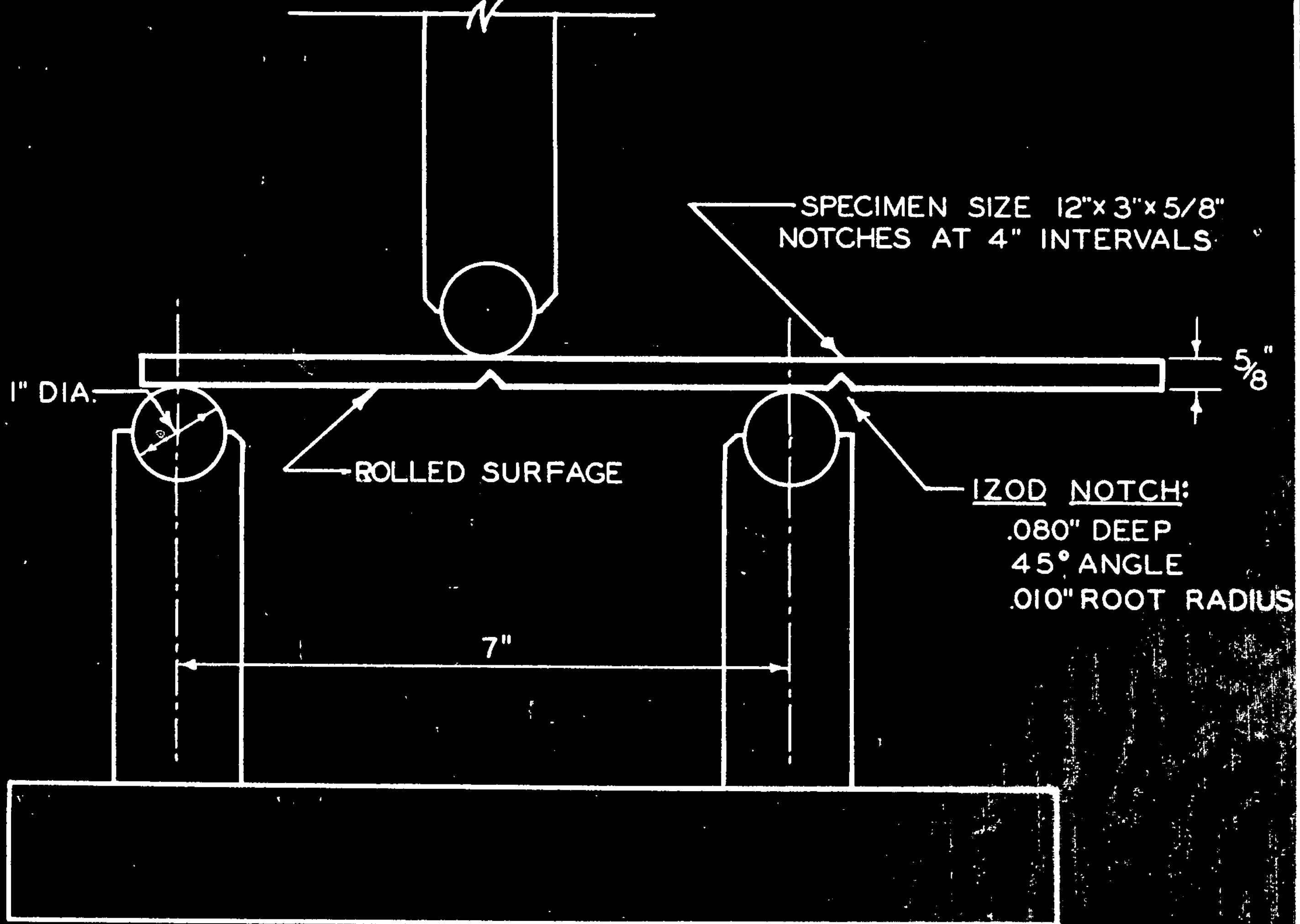


FIG. 2 THE LEHIGH SLOW NOTCHED BEND TEST

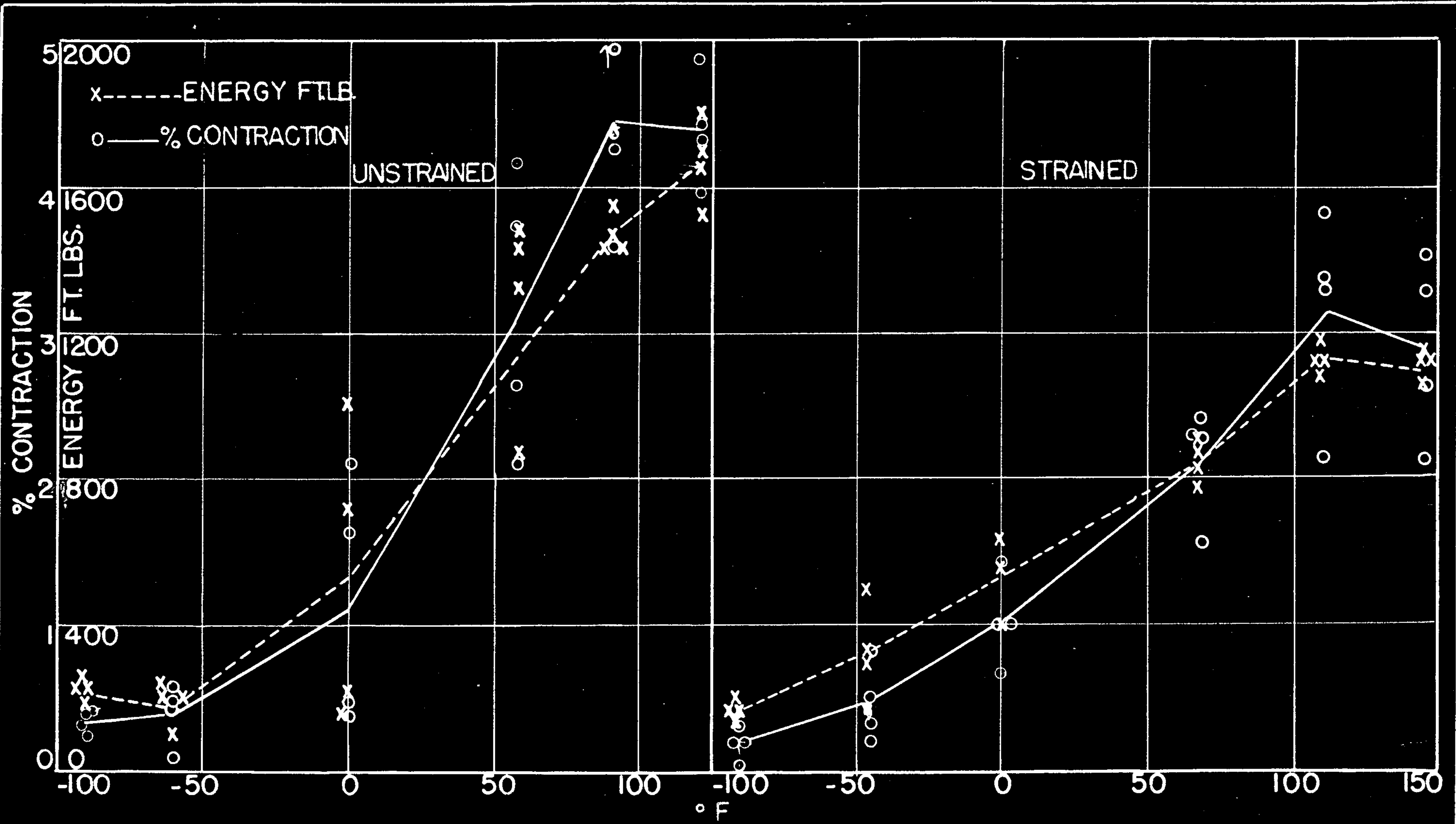


FIG. 3 COMPARISON OF % CONTRACTION AND ENERGY CURVES FOR WELDED A-201, 5/8" MATERIAL

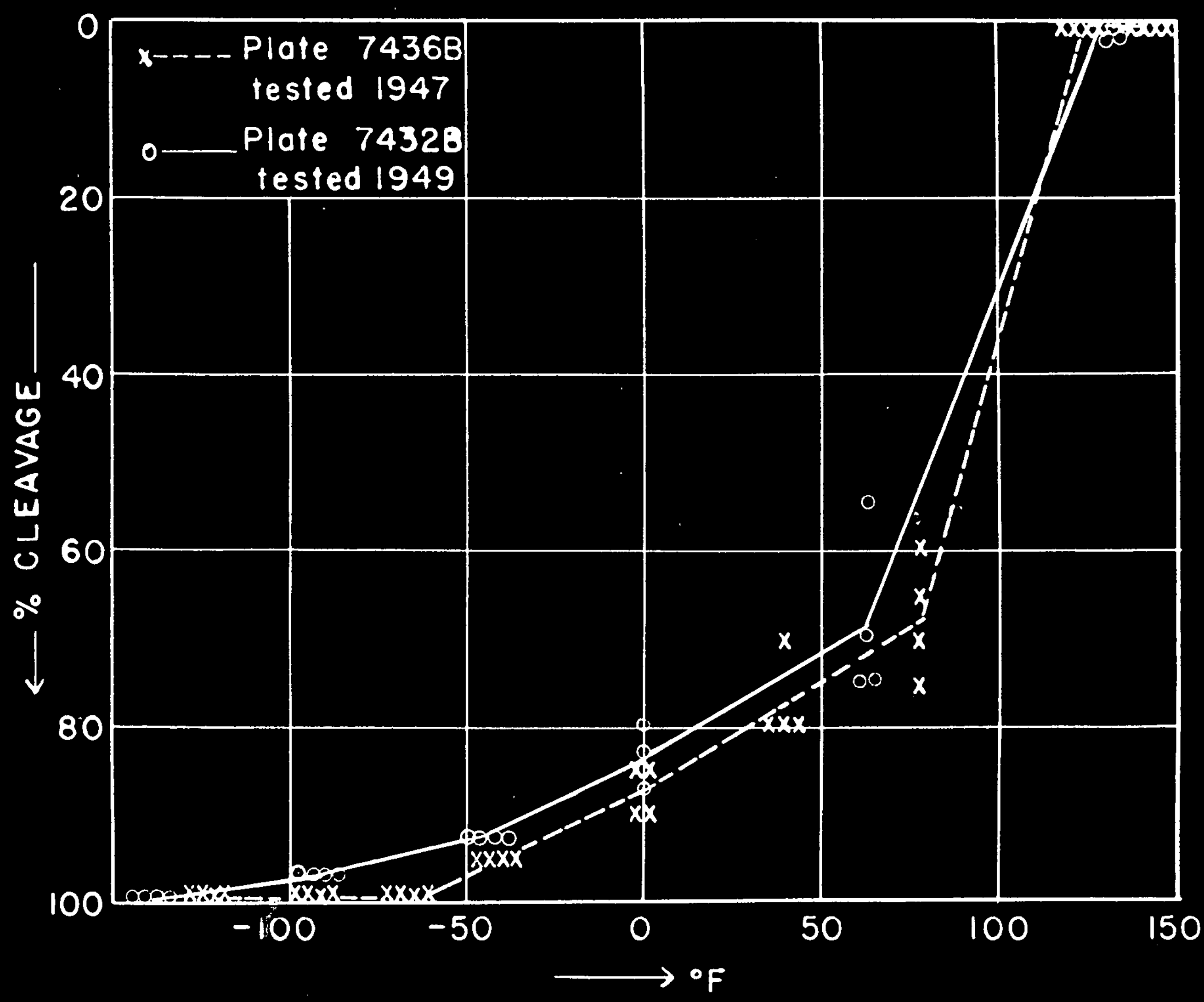


FIG. 4 TRANSITION CURVES FOR SAME A-201, 1 1/4" MATERIAL DETERMINED IN 1947 AND 1949.

LEHIGH SLOW NOTCHED - BEND TEST

CRITERION : % CLEAVAGE

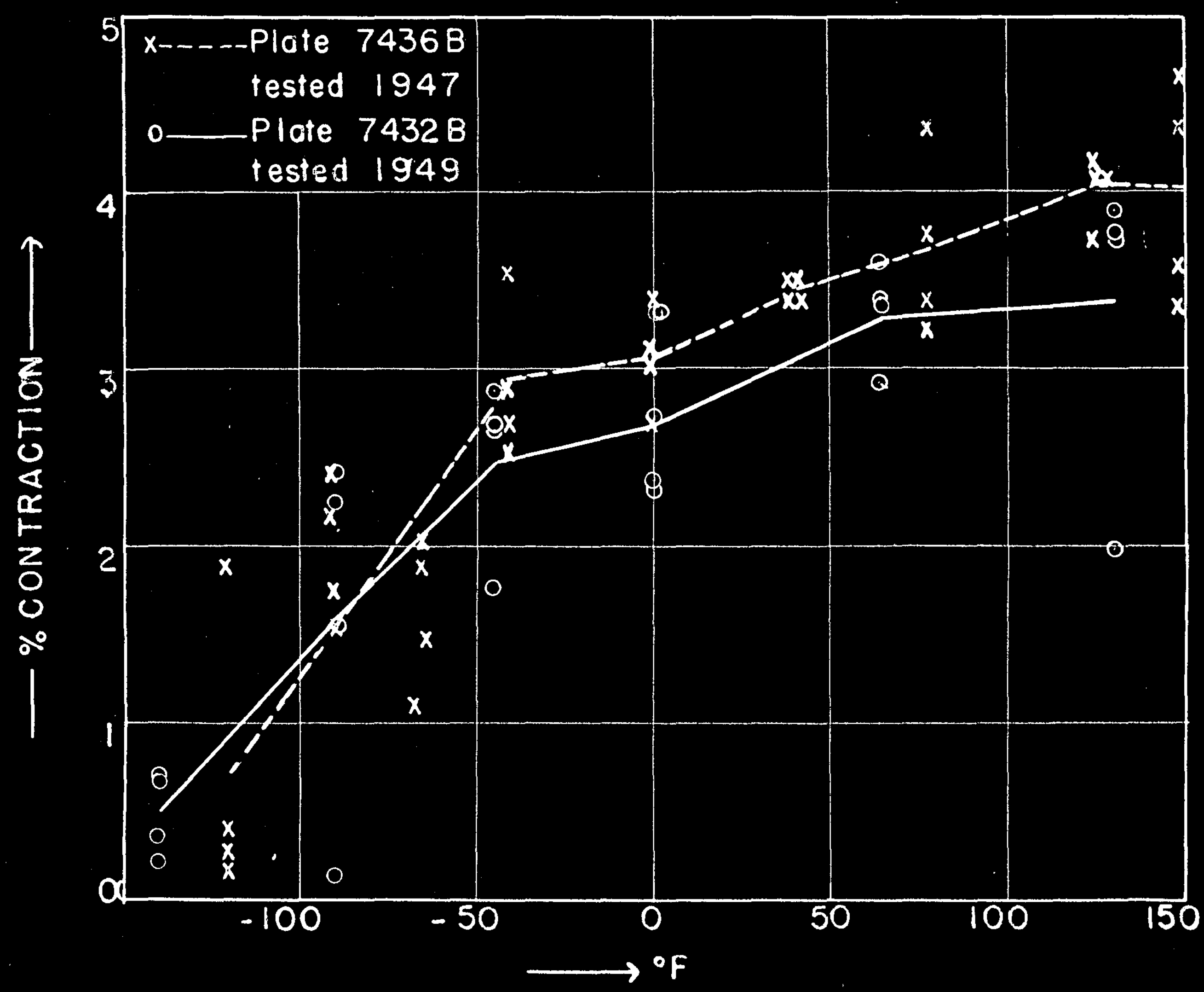


FIG. 5 TRANSITION CURVES FOR SAME A-201, 1 1/4" MATERIAL DETERMINED IN 1947 AND 1949.

LEHIGH SLOW NOTCHED-BEND TEST

CRITERION: % CONTRACTION

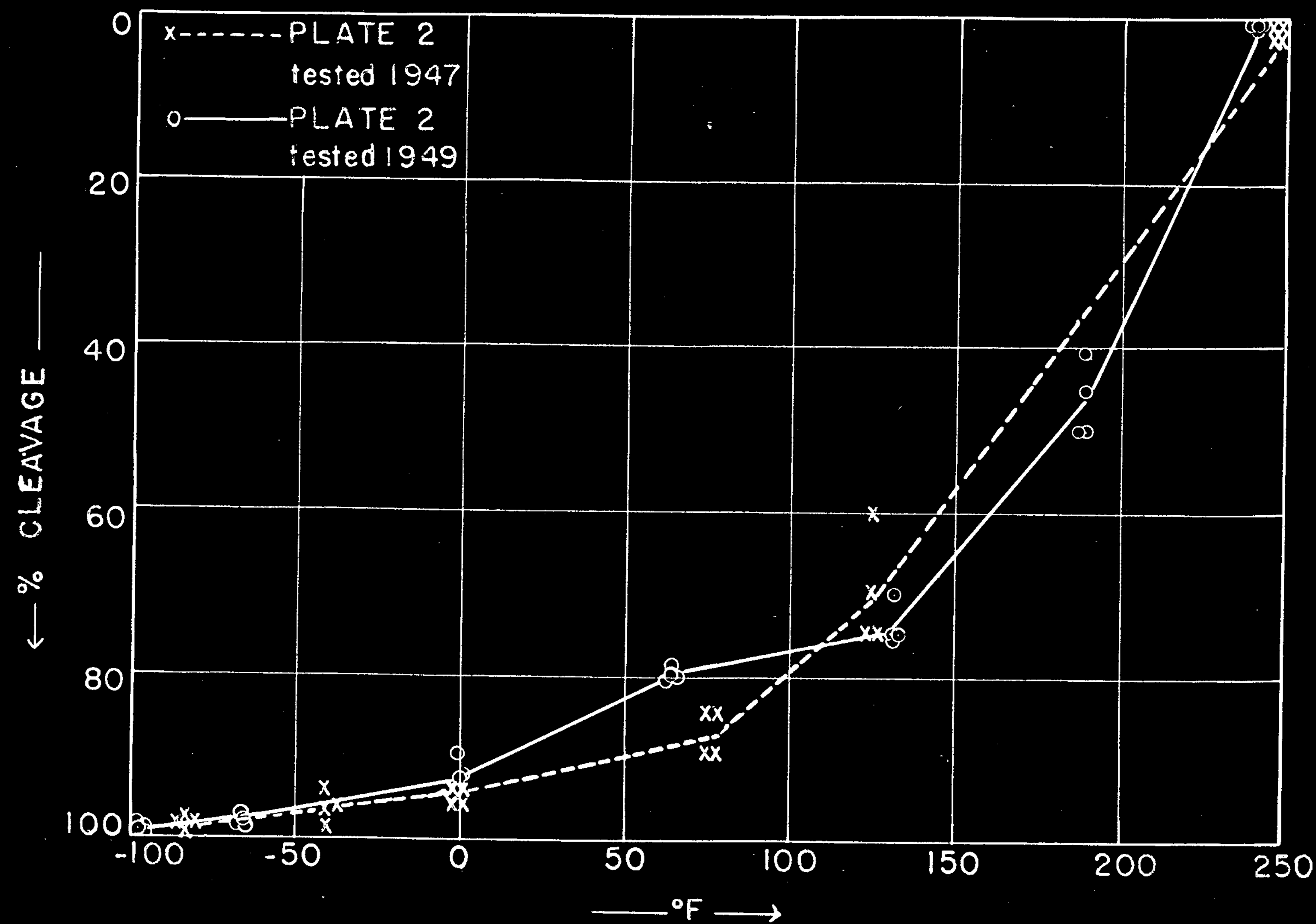


FIG. 6 TRANSITION CURVES FOR SAME A-70, 1 1/4" MATERIAL DETERMINED IN 1947 AND 1949

LEHIGH SLOW NOTCHED - BEND TEST CRITERION: % CLEAVAGE

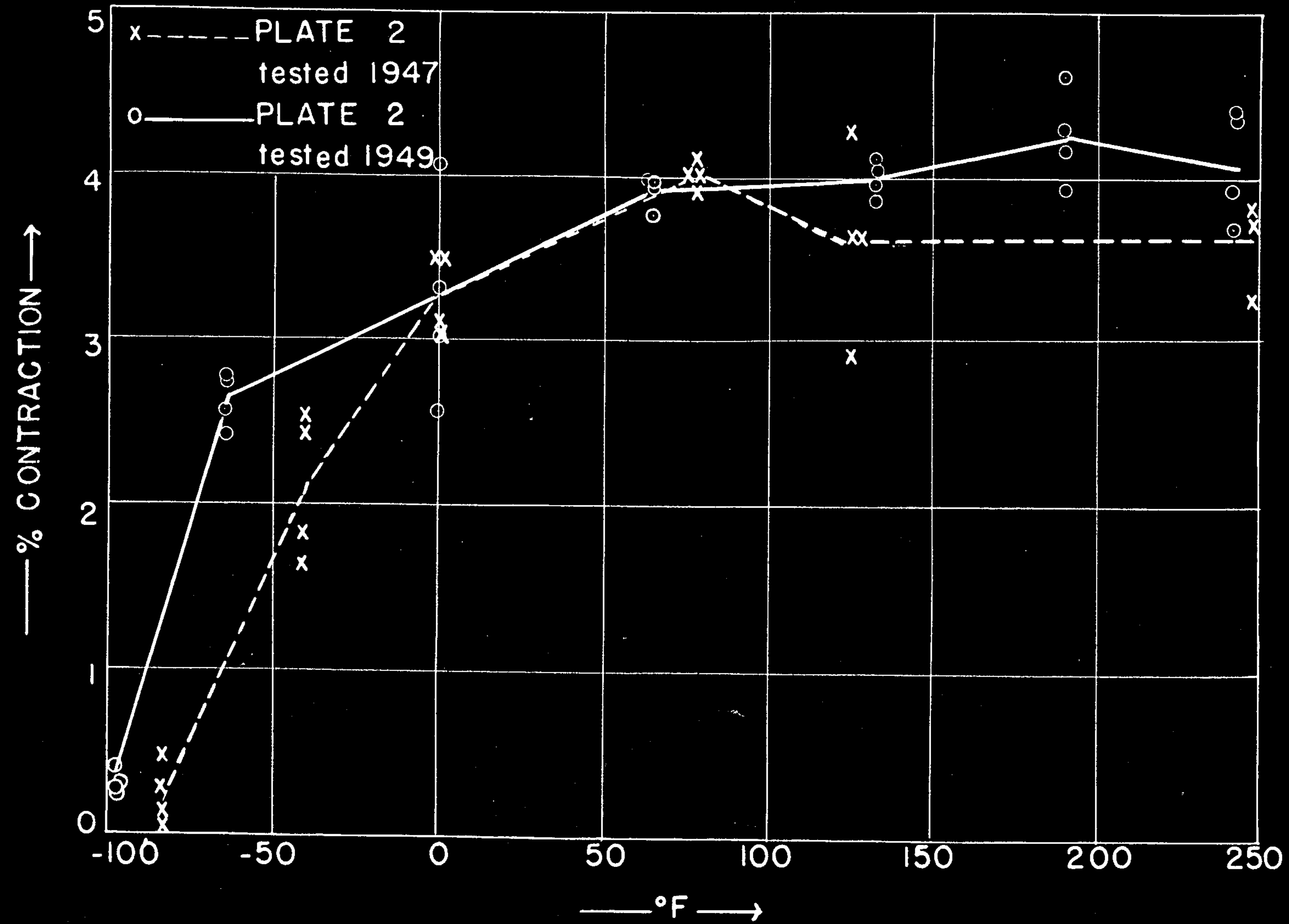


FIG. 7 TRANSITION CURVES FOR SAME A-70, 1 1/4" MATERIAL DETERMINED IN 1947 AND 1949

LEHIGH SLOW NOTCHED-BEND TEST CRITERION: %CONTRACTION

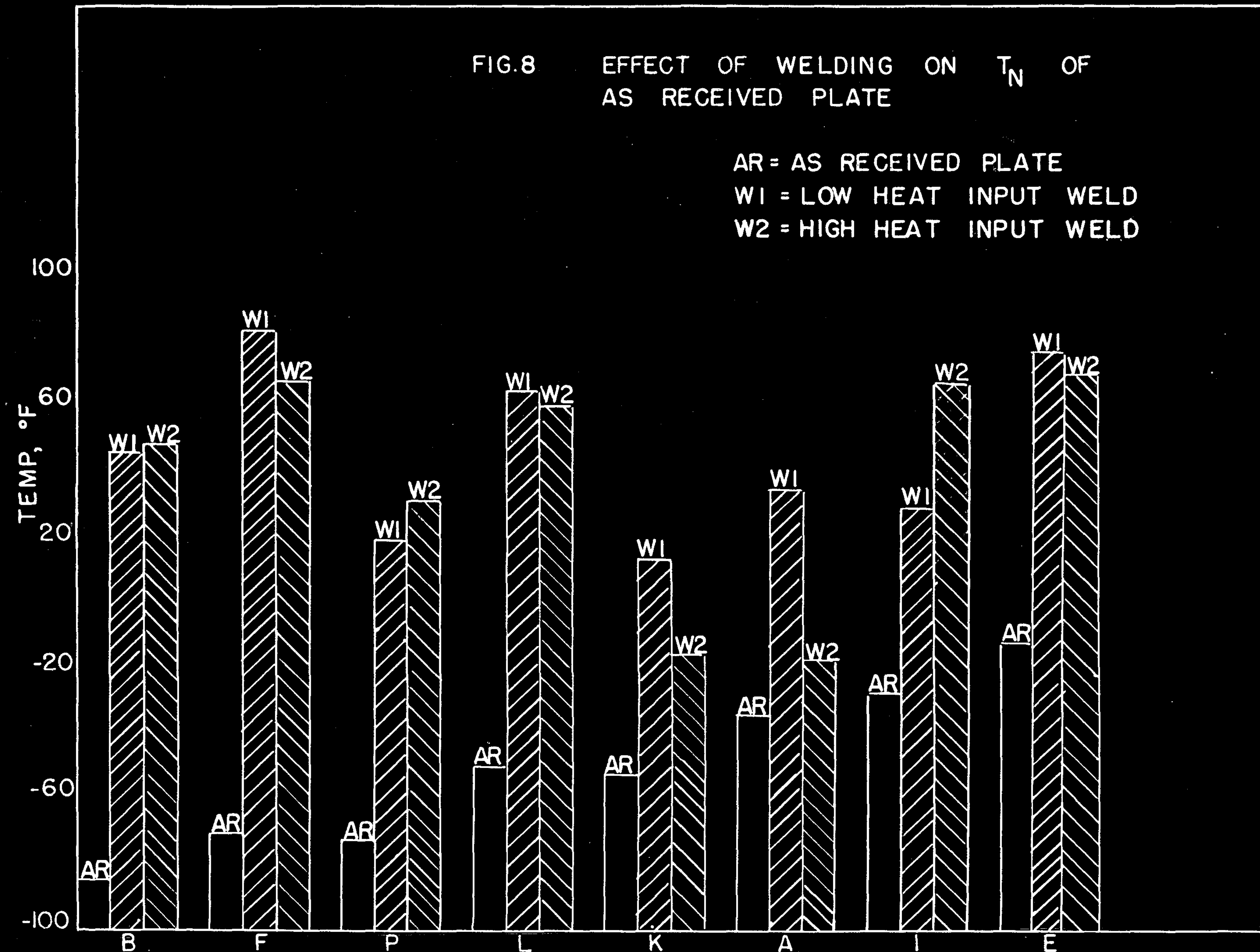


FIG.8 EFFECT OF WELDING ON T_N OF AS RECEIVED PLATE
AR = AS RECEIVED PLATE
W1 = LOW HEAT INPUT WELD
W2 = HIGH HEAT INPUT WELD
TEMP, °F
100
60
20
-20
-60
-100
AR
W1
W2
B
F
P
L
K
A
I
E

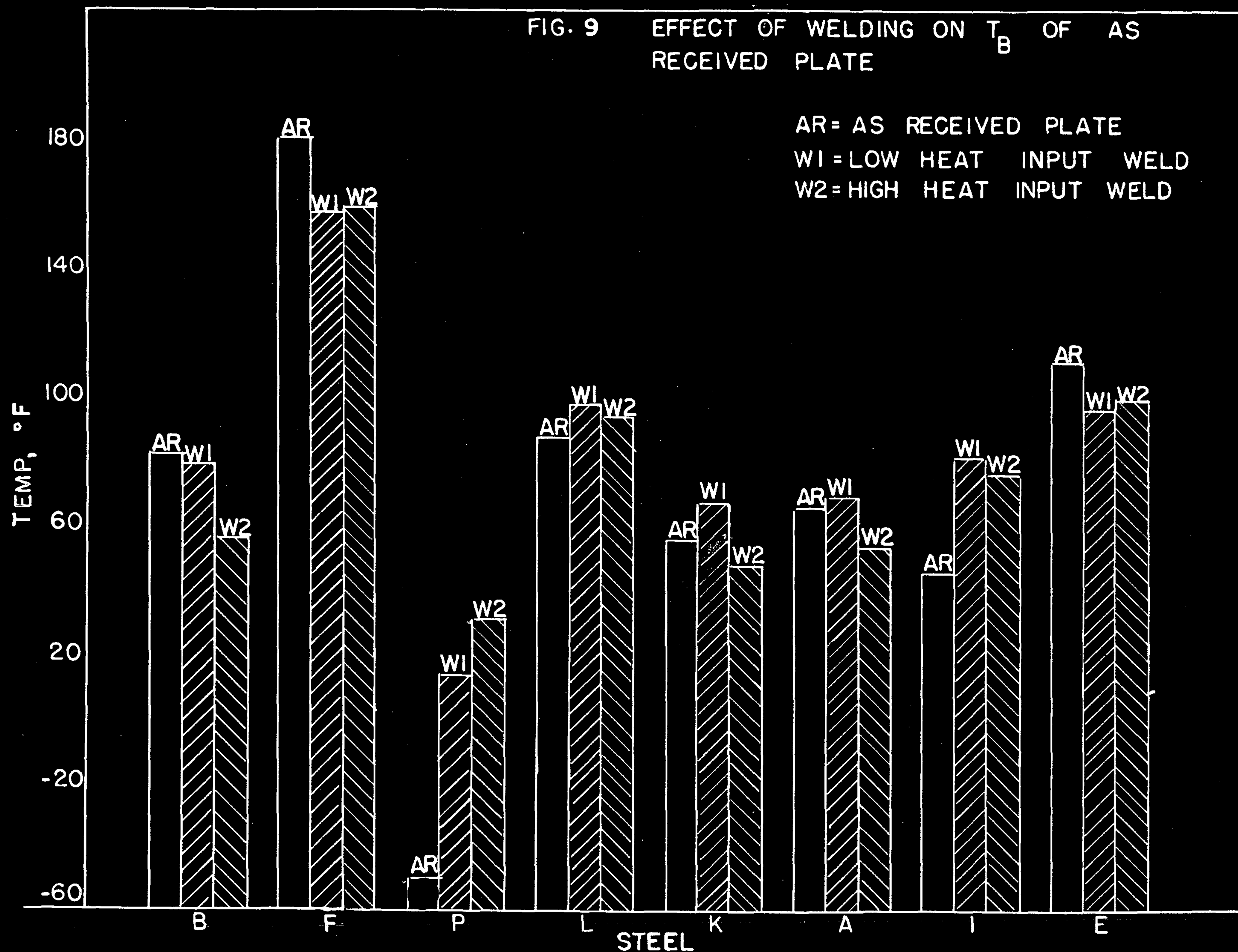


FIG. 9 EFFECT OF WELDING ON T_B OF AS RECEIVED PLATE

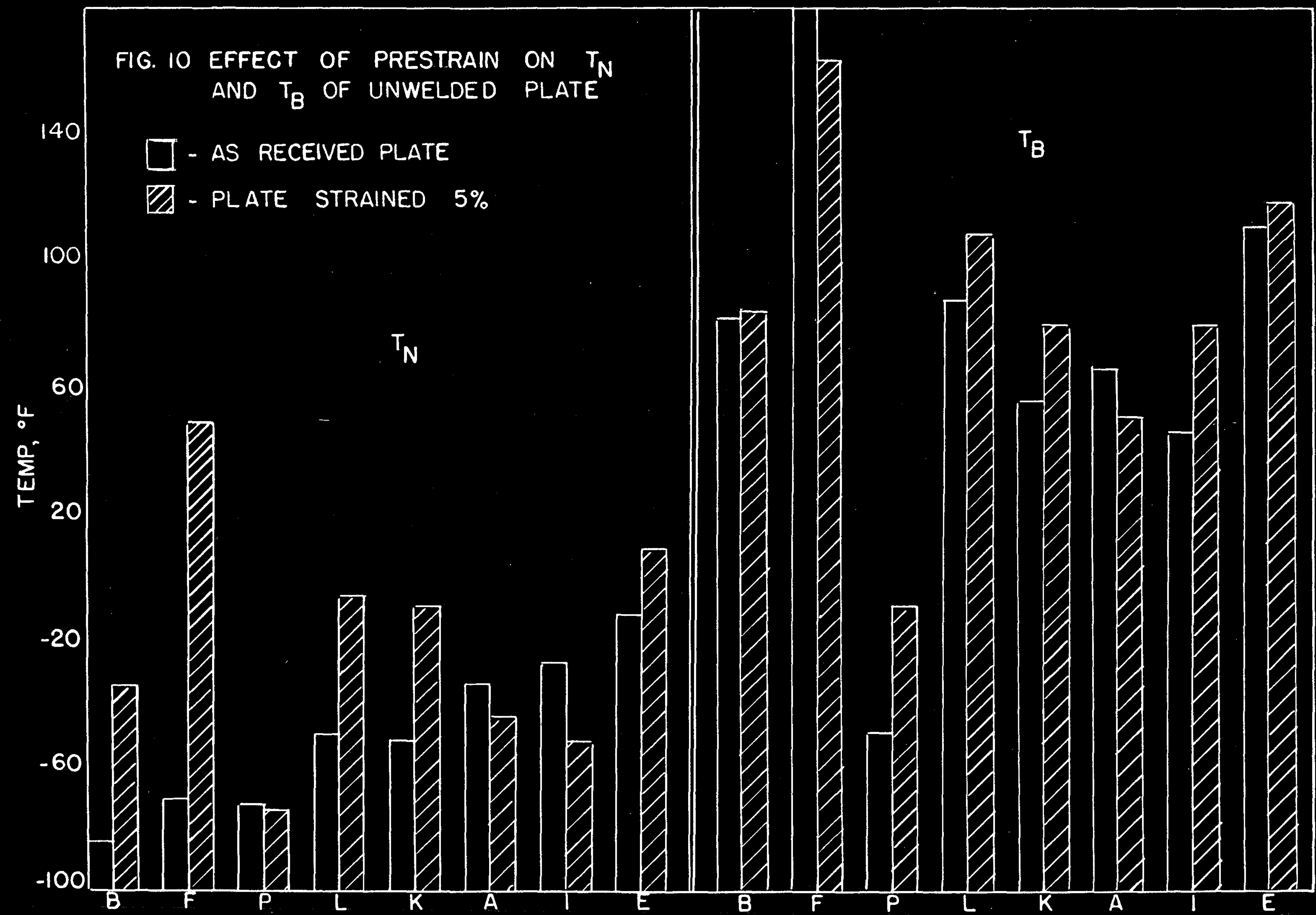


FIG. 10 EFFECT OF PRESTRAIN ON T_N AND T_B OF UNWELDED PLATE
- AS RECEIVED PLATE
- PLATE STRAINED 5%
T_N
T_B
TEMP, °F
140
100
60
20
-20
-60
-100
B F P L K A I E B F P L K A I E

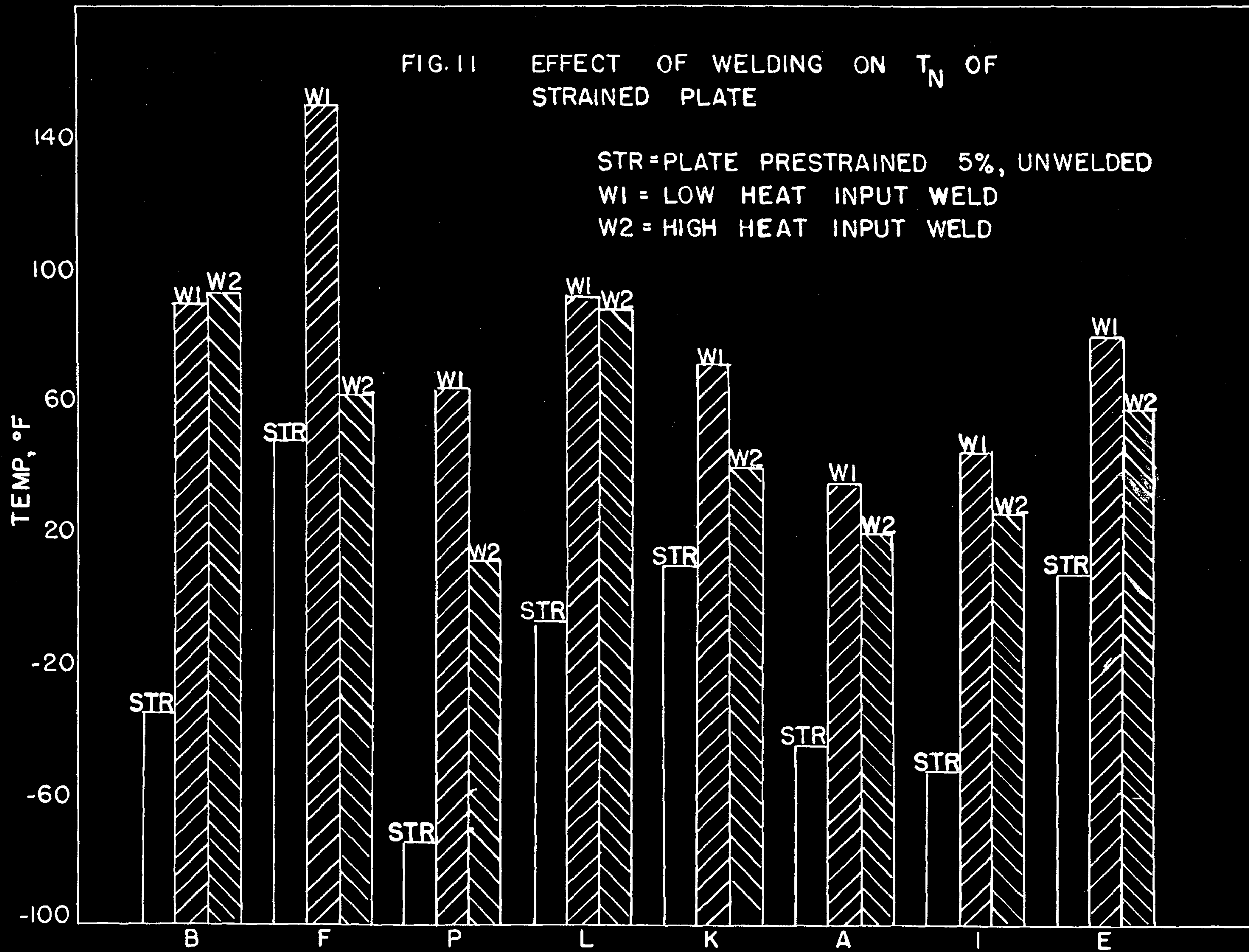


FIG. 11 EFFECT OF WELDING ON T_N OF STRAINED PLATE
STR = PLATE PRESTRAINED 5%, UNWELDED
W1 = LOW HEAT INPUT WELD
W2 = HIGH HEAT INPUT WELD
TEMP, °F
140
100
60
20
-20
-60
-100
STR
W1
W2
B
F
P
L
K
A
I
E

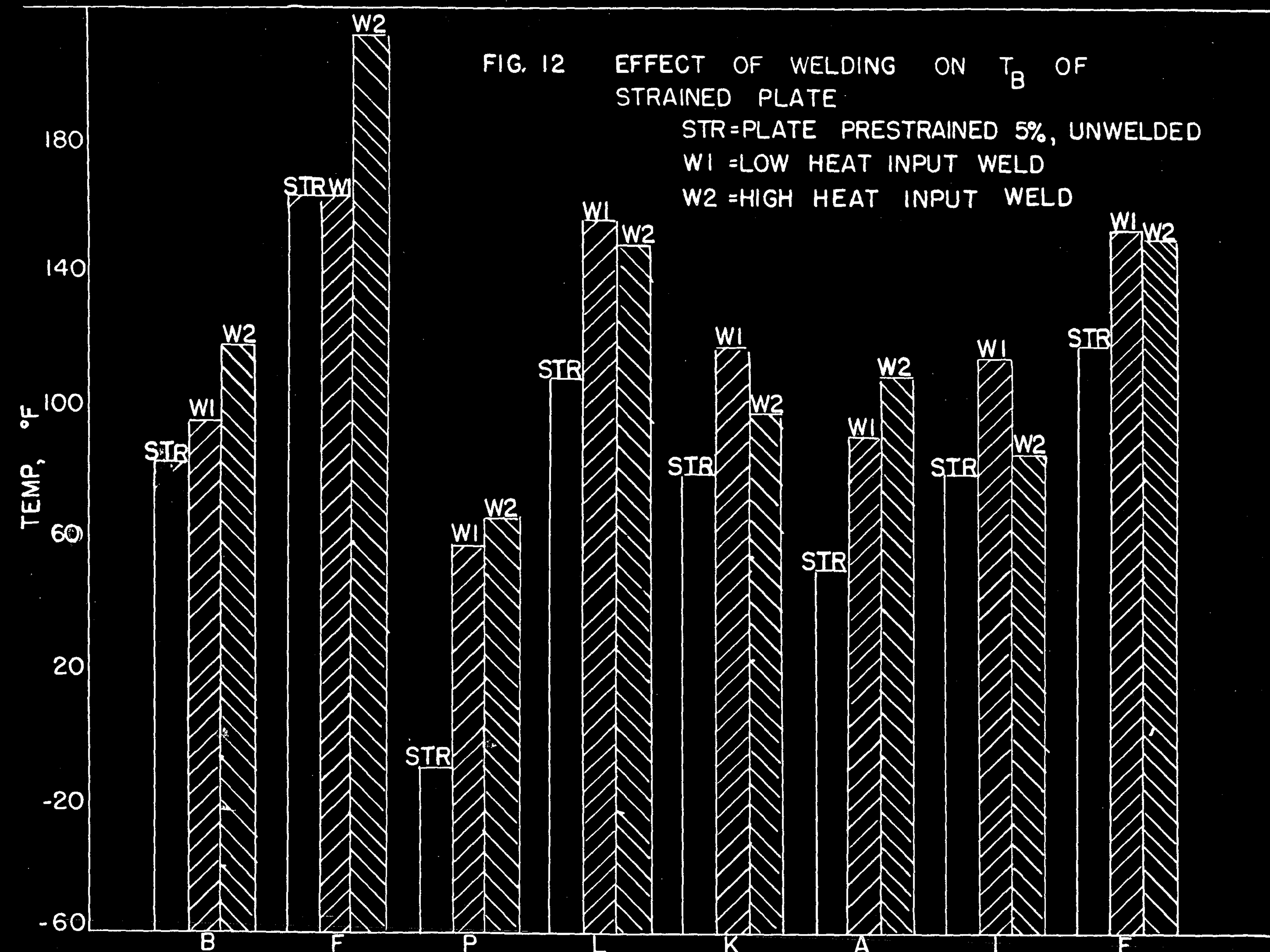


FIG. 12 EFFECT OF WELDING ON T_B OF STRAINED PLATE
STR=PLATE PRESTRAINED 5%, UNWELDED
W1 =LOW HEAT INPUT WELD
W2 =HIGH HEAT INPUT WELD
TEMP, °F
180
140
100
60
20
-20
-60
STR
W1
W2
B
F
P
L
K
A
I
E

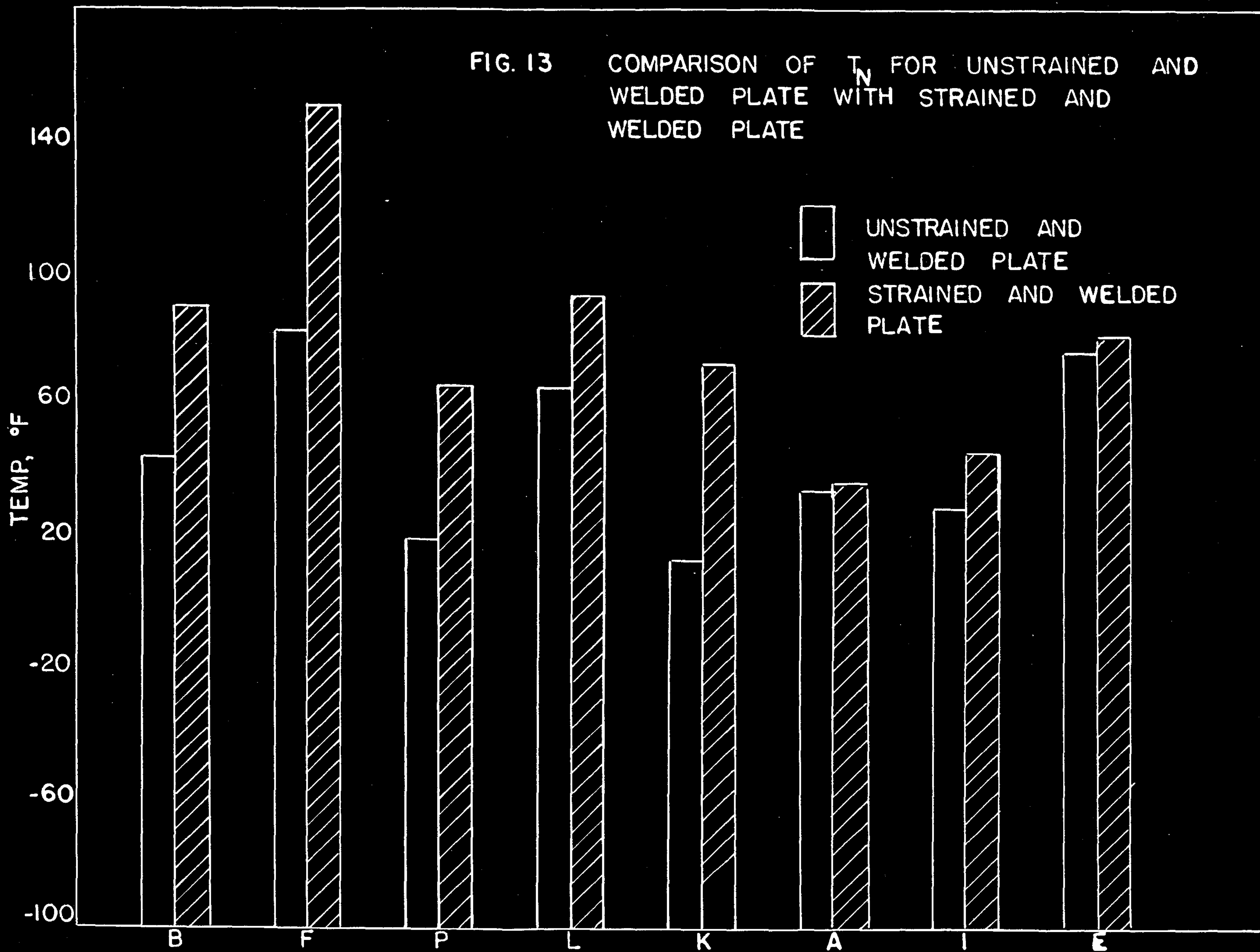
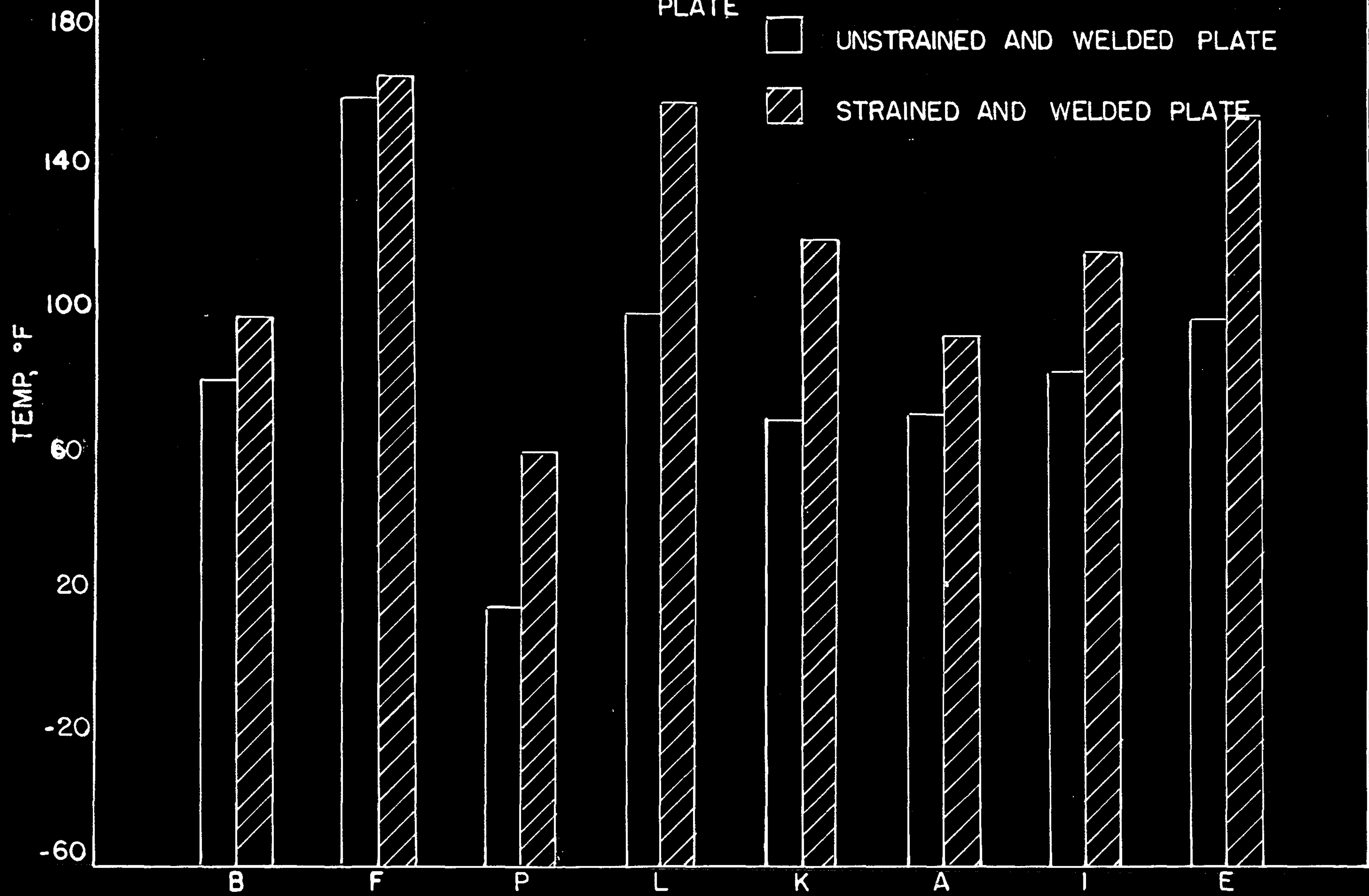


FIG. 13 COMPARISON OF T_N FOR UNSTRAINED AND WELDED PLATE WITH STRAINED AND WELDED PLATE

FIG. 14 COMPARISON OF T_B FOR UNSTRAINED AND WELDED PLATE WITH STRAINED AND WELDED PLATE



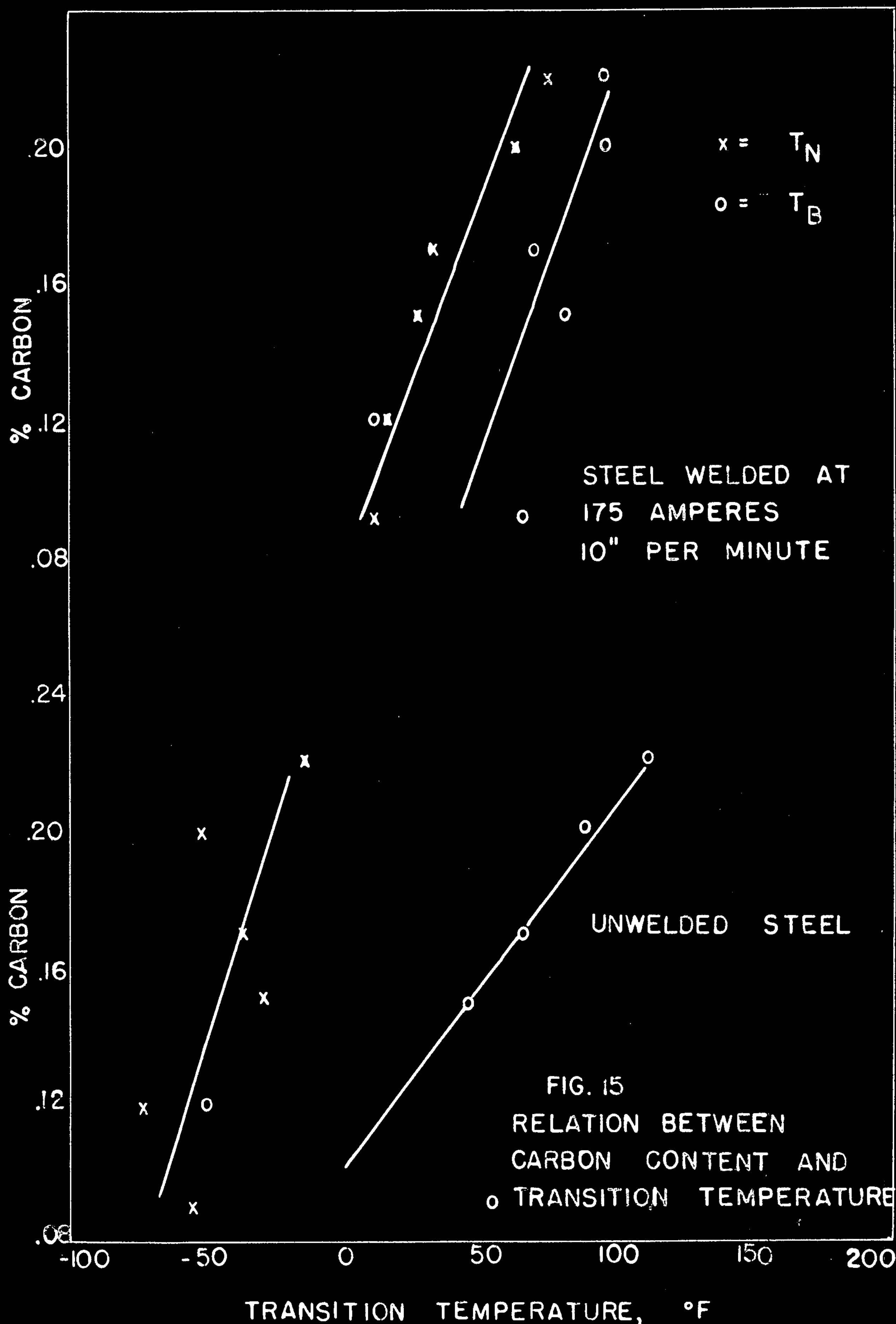


FIG. 15
RELATION BETWEEN
CARBON CONTENT AND
TRANSITION TEMPERATURE

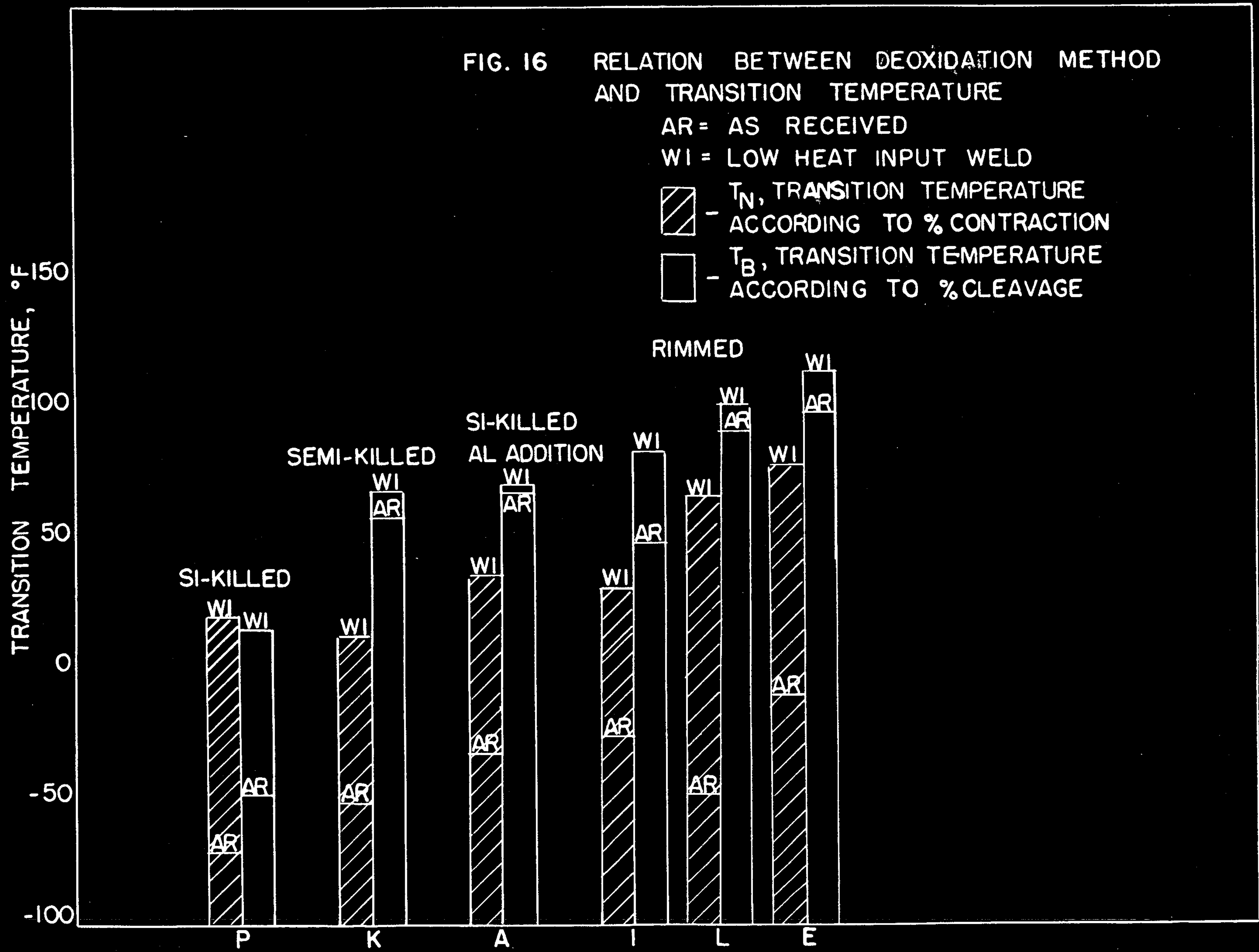


FIG. 16 RELATION BETWEEN DEOXIDATION METHOD AND TRANSITION TEMPERATURE

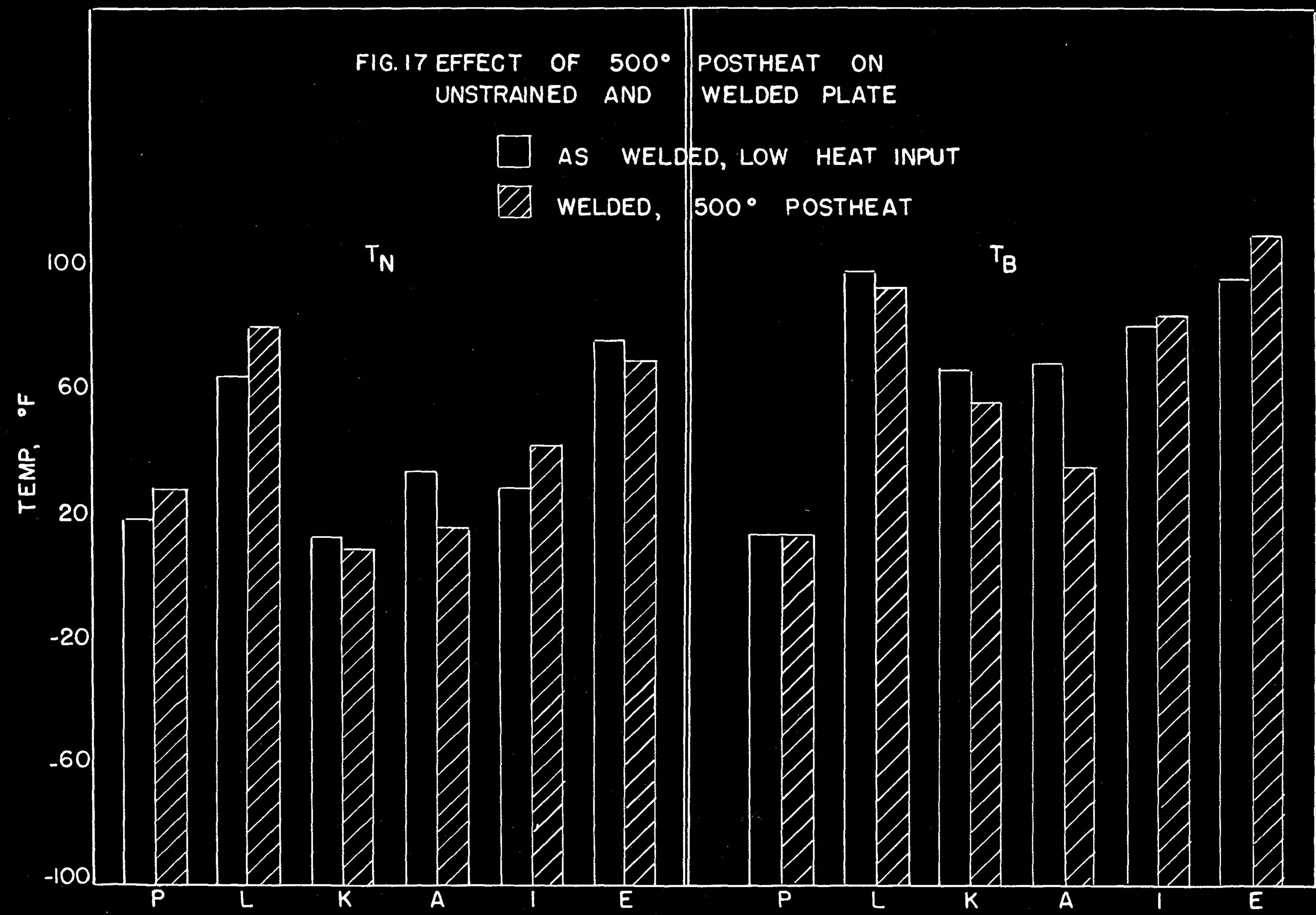


FIG. 17 EFFECT OF 500° POSTHEAT ON UNSTRAINED AND WELDED PLATE
AS WELDED, LOW HEAT INPUT
WELDED, 500° POSTHEAT
T_N
T_B
TEMP, °F
100
60
20
-20
-60
-100
P
L
K
A
I
E
P
L
K
A
I
E

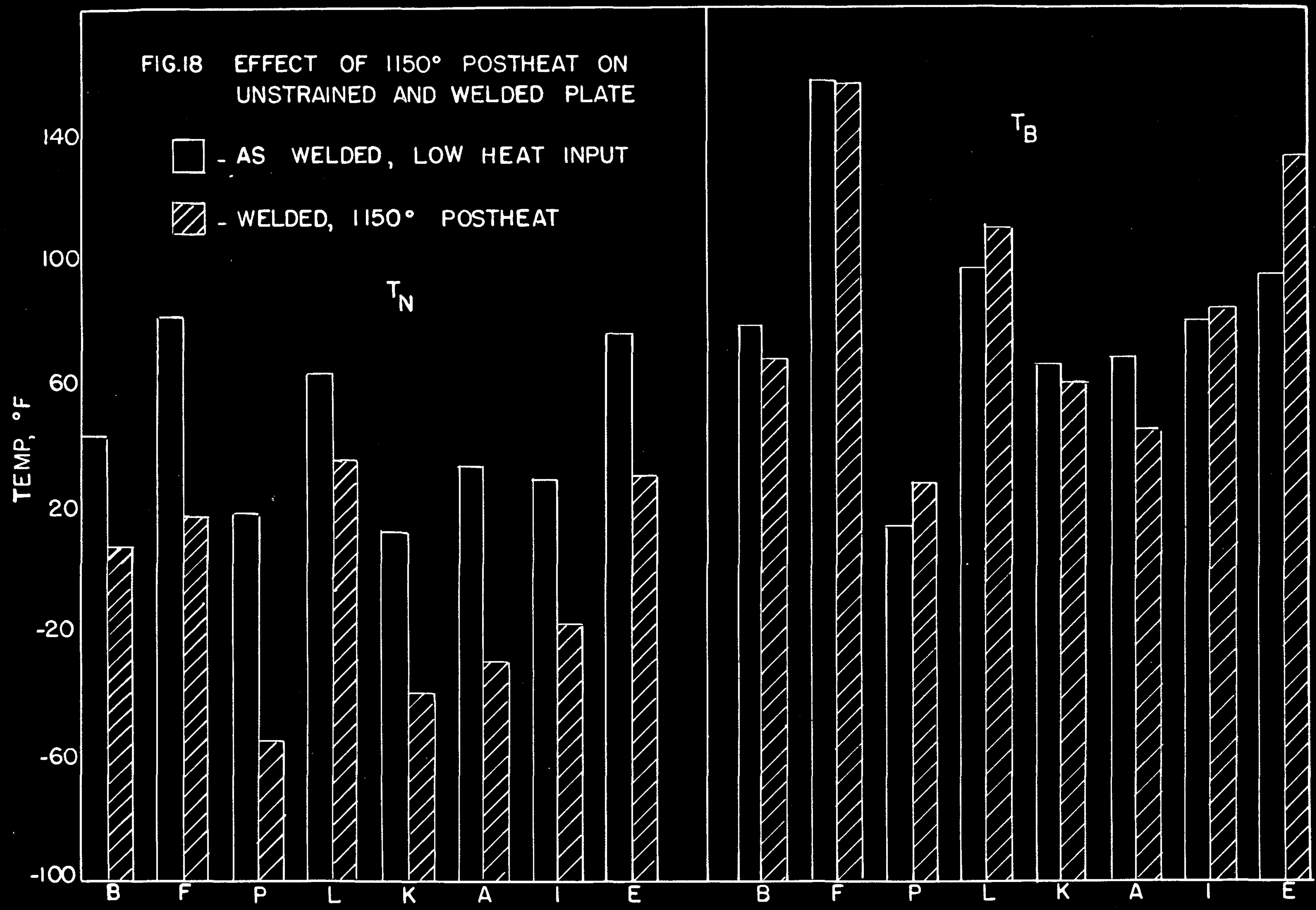


FIG.18 EFFECT OF 1150° POSTHEAT ON UNSTRAINED AND WELDED PLATE

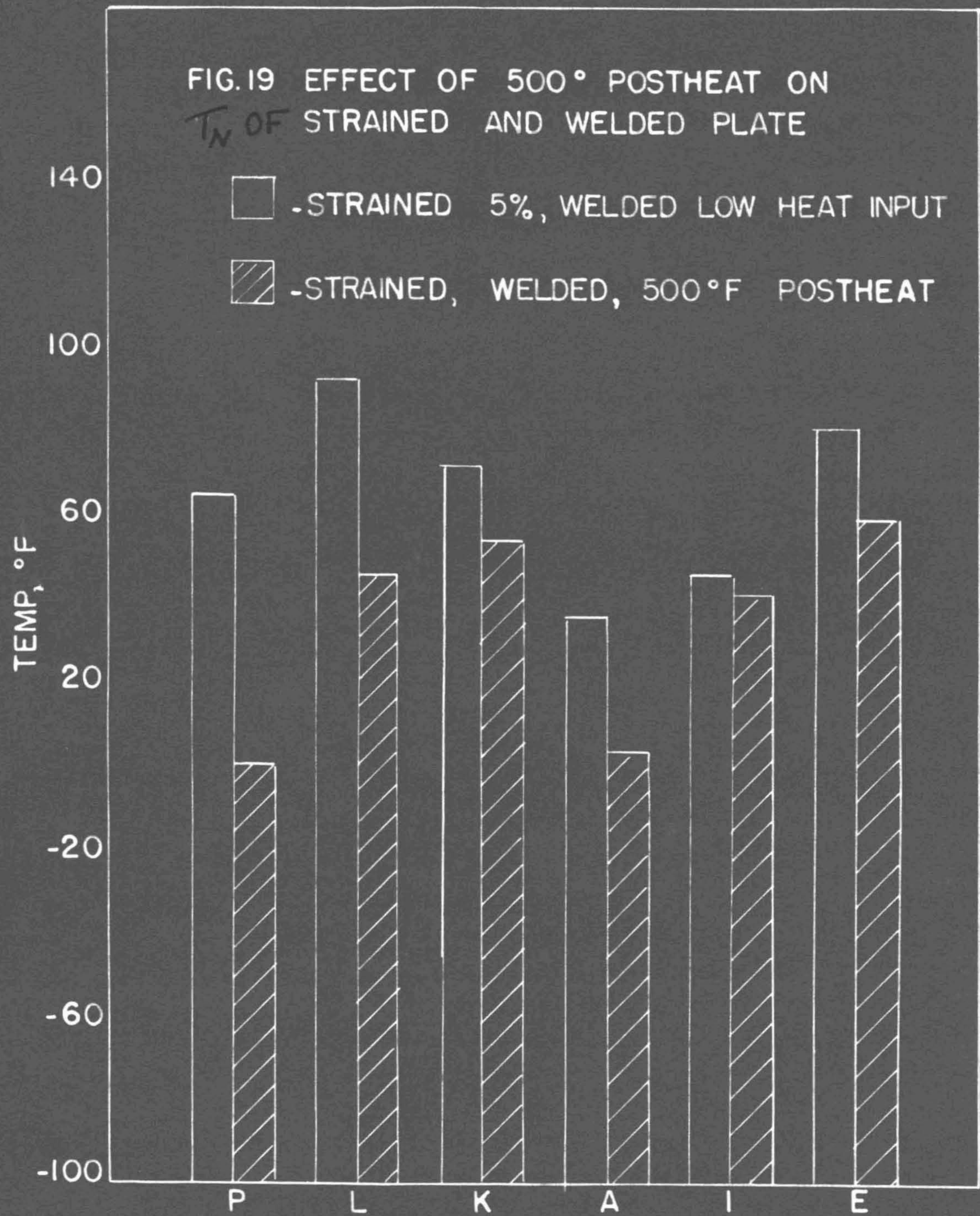


FIG. 19 EFFECT OF 500° POSTHEAT ON T_N OF STRAINED AND WELDED PLATE

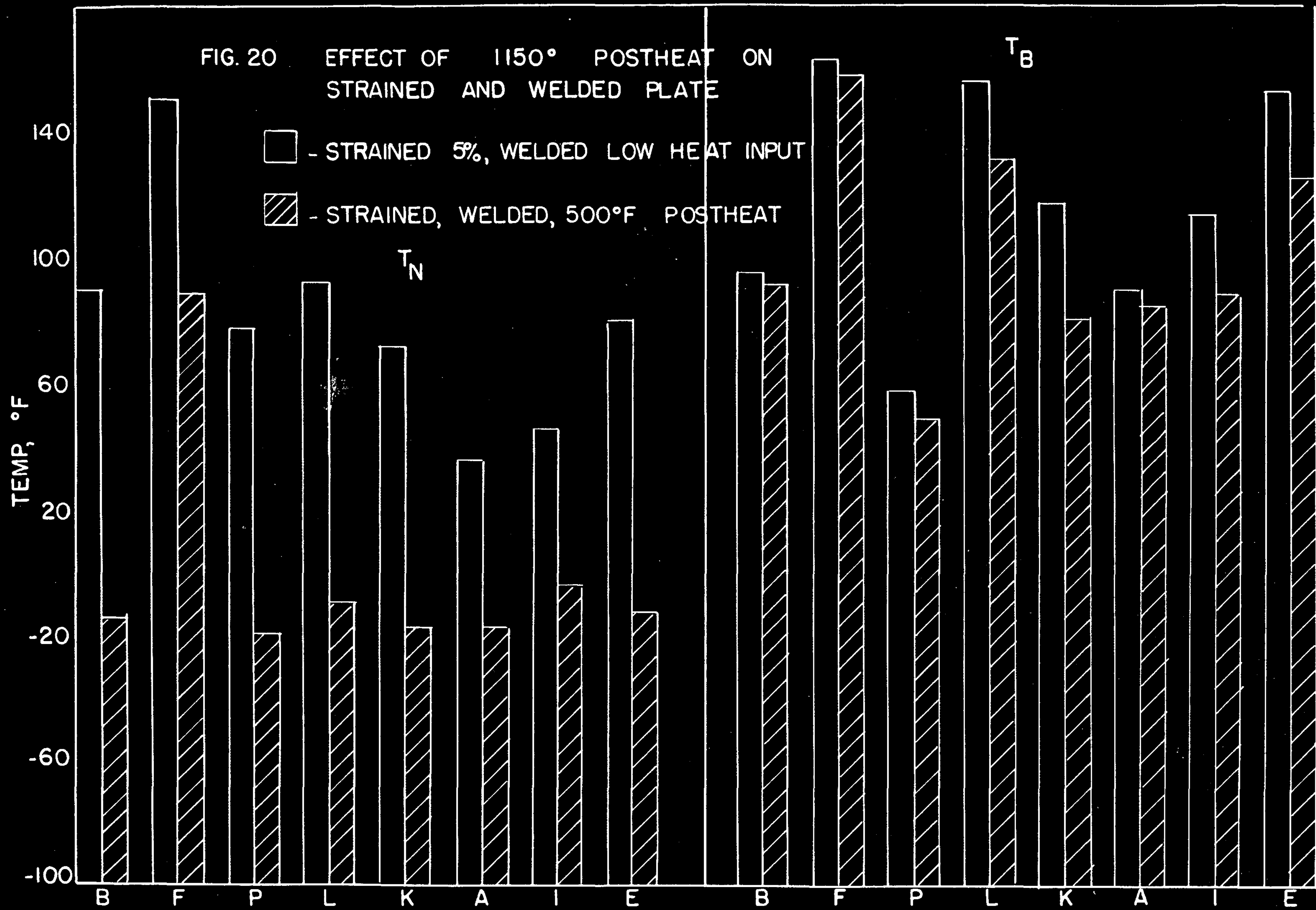


FIG. 20 EFFECT OF 1150° POSTHEAT ON STRAINED AND WELDED PLATE
- STRAINED 5%, WELDED LOW HEAT INPUT
- STRAINED, WELDED, 500°F POSTHEAT
T_N
T_B
TEMP, °F
140
100
60
20
-20
-60
-100
B F P L K A I E
B F P L K A I E