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THE TEE-BEND TEST TO COMPARE THE WELDING QUALITY OF STEELS

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ABSTRACT

A bend test for comparing the welding quality of steels is described in this paper. Specimens of fillet-welded T-sections of a number of low-alloy high-tensile steels were bent in special testing jigs at room temperature and at temperatures as low as −20° F. Several criteria, such as maximum load, angle at maximum load, type and location of fractures, were used to compare the specimens. A special method of statistical analysis, which is described in detail in the paper, was used to evaluate the data and to compare and rate the welding quality of the steels.

CONTENTS

I. INTRODUCTION

In recent years there has been a marked increase in the use of welded in place of riveted construction, particularly for the fabrication of ships. This change involved more than a simple substitution of one method for another. The design for riveted construction is not necessarily equally suitable for welding, and the most effective use of material in welded construction is obtained only when the requirements for this method are well understood and provided for in the design.

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Furthermore, all steels or other constructional metals are not equally well adapted to joining by welding. There is no "best" steel for welding nor a "best" welding method or technique, but a best combination of these interrelated factors can be determined for any metal that is weldable. In selecting the metal best adapted to the strength requirements of the design and utility of a structure to be assembled by welding, the welding quality of the metal, within the limitations imposed by the practicability of the welding method, is of prime importance.

With proper attention to design and welding technique, little difficulty need be encountered in welding medium steel by fusion processes.

In 1933, the Bureau of Construction and Repair (now a part of the Bureau of Ships) of the Navy Department and the National Bureau of Standards started a cooperative investigation of the welding quality of steels considered suitable for naval construction. Particular attention was to be given to "high tensile" low-alloy steels, of which numerous varieties and types have since been announced by manufacturers.[1 2 3 4 5] A further requirement was that strong ductile joints should be obtained by the electric-arc welding process with low-carbon steel, Navy Grade EA electrodes, and without preheating or postheating.

The strength properties of welded joints can readily be determined by well-established methods. The relationships between "ductility" in a welded joint and the welding quality of the steel were not clearly defined, and methods for making the mechanical tests of a specimen from a welded joint to evaluate ductility were not well established. It was considered, however, that some form of bend test would be the most nearly suitable for this purpose.

It is generally agreed that ability to bend in the plastic-deformation range is evidence of ductility in a metal, whether in a weld or in an otherwise fabricated form. The full ductility of a metal may not be realized in a bend test of a specimen because of local stress conditions peculiar to the geometrical shape of the specimen. Free bends and guided bends in jigs have been used widely for face, root, or side bends of butt-welded joints. Often the faces of the welds are machined for these types of test.

For the purpose of this investigation, it was decided that the most informative results would be obtained from a guided bend test, in a jig, of a double-fillet T-welded specimen, without removing any metal from the face of the welds. Justification for this decision was had in the fact that this type of joint is one of the most widely used in ship-hull construction, and furthermore, the ability of the specimen to withstand bending distortion in the welded areas, without rupture, is an indication that such a joint can absorb a proportionate share of the distortion of the structure as a whole.

Ability to withstand severe distortions without premature or brittle-type ruptures, particularly in the joints, is a highly desirable, in fact a necessary, feature in ship-hull structures. It is not to be expected,

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1 H. W. Gillett, *Trends in the metallurgy of low-alloy, high-strength structural steels*, Role of Metals in New Transportation Symposium, Metals Tech. **3**, 40 (1936).

2 Edwin F. Cone, *Carbon and low-alloy steels*, Symposium on High Strength Constructional Metals, p. 1 (Am. Soc. Testing Materials, Philadelphia, Pa.).

3 *Low-alloy, high strength structural steels—An extended abstract*, Metals & Alloys **7**, 77 (1936).

4 *The present status of the low-alloy, high-strength steels—A survey*, Metals & Alloys **9**, 243 (1938).

5 *The present status of the low-alloy, high-strength steels—A survey*, Metals & Alloys **13**, 273 (1941).

however, that the maximum angle of bend, or any other numerical value obtained from a bend test on a welded joint, is a direct measure of the amount of distortion the joint can withstand in the assembled structure. These values were used in this investigation as a means of comparison, on a common basis, of the welding qualities of a number of structural steels, as shown by certain properties related to the service requirements of the welds.

This paper describes the steels and preparation of the welded specimens and the procedure for making the bend tests, and describes and discusses the methods for evaluating the welding quality of the steels from the results of the bend tests and other metallurgical and mechanical properties of the welds and of the steels themselves.

II. MATERIALS

The steels to be tested included several medium- and low-alloy "high tensile" steels available at that time. The following tensile properties were desired for the steels:

Yield point, minimum	50,000 lb/in.^{2}
Tensile strength, minimum	70,000 lb/in.^{2}
Elongation in 8 in., minimum	20 percent.

Each steel was to be secured in three thicknesses of plates, ¼, ½, and ¾ in., and was to be welded in the as-rolled condition and after normalizing at 1,650° F. for 1 hour. It was also desired that all of the plates of each steel should be rolled from the same heat.

The chemical compositions of the steels are given in table 1.

TABLE 1.—*Chemical composition of the steels* [a]

Steel	Thickness	Percentage of—									
		C	Mn	P	S	Si	Ni	Cr	V	Mo	Cu
	In.										
	¼	0.14	0.46	0.014	0.025	0.18	------	------	------	------	0.23
138	½	.14	.46	.013	.024	.17	------	------	------	------	.22
	¾	.14	.46	.015	.025	.17	------	------	------	------	.23
	¼	.20	.69	.019	.036	.18	------	------	------	------	.20
139	½	.20	.70	.022	.036	.17	------	------	------	------	.20
	¾	.19	.68	.020	.034	.18	------	------	------	------	.23
	¼	.26	.66	.014	.030	.17	------	------	------	------	.22
140	½	.26	.67	.015	.031	.17	------	------	------	------	.23
	¾	.26	.66	.013	.030	.17	------	------	------	------	.24
	¼	.17	.44	.019	.030	.13	0.07	------	------	0.09	.16
141	½	.20	.70	.017	.032	.19	.08	------	------	.09	.19
	¾	.20	.70	.017	.032	.19	.08	------	------	.09	.19
	¼	.14	.61	.011	.035	.19	1.28	0.06	0.09	------	.04
143	½	.14	.62	.012	.035	.19	1.30	.06	.09	------	.04
	¾	.14	.61	.011	.035	.19	1.28	.06	.09	------	04
	¼	.18	.99	.017	.030	.17	------	.05	.07	------	.16
144	½	.17	1.25	.033	.028	.21	------	------	.12	------	.15
	¾	.17	1.25	.031	.027	.21	------	------	.12	------	.15
	¼	.10	.75	.011	.027	.17	.26	------	------	.46	.11
145	½	.08	.76	.011	.028	.15	.27	------	------	.44	.10
	¾	.17	.83	.021	.030	.24	.09	------	------	.44	.12
	¼	.10	.44	.012	.023	.16	1.92	------	------	------	1.06
146	½	.09	.42	.014	.019	.17	1.94	------	------	------	1.00
	¾	.10	.38	.015	.019	.16	1.90	------	------	------	1.01

[a] The chemical analyses were made at the Material Laboratory, Naval Gun Factory, Washington, D. C.

TABLE 1.—*Chemical composition of the steels—Continued*

Steel	Thickness	Percentage of—									
		C	Mn	P	S	Si	Ni	Cr	V	Mo	Cu
	In.										
147	¼	0.11	0.57	0.015	0.023	0.15	2.03	0.02	------	------	1.08
	½	.14	.57	.014	.025	.14	1.99	.02	------	------	1.02
	¾	.14	.57	.014	.024	.15	1.95	.02	------	------	1.08
148	¼	.11	.76	.106	.026	.02	0.71	------	------	0.11	1.74
	½	.09	.75	.097	.024	.06	.72	------	------	.10	1.63
	¾	.08	.76	.101	.029	.06	.68	------	------	.11	1.76
149	¼	.10	.66	.126	.023	.16	.60	------	------	------	1.00
	½	.09	.56	.112	.023	.17	.59	------	------	------	1.04
	¾	.11	.56	.109	.023	.17	.60	------	------	------	1.16
150	¼	.14	.59	.014	.026	.16	2.32	------	------	.12	0.13
	½	.16	.59	.014	.026	.18	1.90	------	------	.10	.14
	¾	.19	.54	.014	.044	.18	2.04	------	------	.07	.14
157	¼	.15	.98	.015	.026	.21	.06	.05	0.09	.10	.10
	½	.16	.98	.016	.027	.21	.06	.05	.09	.10	.18
	¾	.15	.96	.015	.028	.22	.07	.05	.09	.10	.10
161	¼	.14	.45	.082	.013	.02	1.82	.14	------	------	.56
	½	.14	.45	.079	.015	.01	1.87	.14	------	------	.58
	¾	.14	.47	.090	.016	.01	1.90	.16	------	------	.54
163	¼	.10	.72	.011	.021	.01	1.30	------	------	.12	1.58
	½	.10	.70	.011	.021	.01	1.30	------	------	.12	1.50
166	½	.09	.59	.012	.018	.003	1.28	------	------	.11	1.15
168	¼	.09	.62	.012	.024	.02	1.37	------	------	.11	1.08
	½	.07	.60	.011	.023	.02	1.36	------	------	.09	1.03
										Zr	
201	b ¼	.13	.66	.027	.023	.73	0.10	.63	------	.14	0.19
	c ¼	.12	.70	.019	.023	.77	.10	.57	------	.13	.20
	b ½	.13	.67	.020	.020	.84	.07	.50	------	.11	.09
	c ½	.13	.69	.019	.027	.87	.14	.64	------	.10	.25

b Plates as rolled
c Plates normalized.

The different thicknesses of steels 141, 144, 145, 148, 149, 150, and 201 were definitely rolled from different heats. The different thicknesses of the remaining steels were probably rolled from single heats.

Tensile properties of the steels are given in table 2.

TABLE 2.—*Tensile properties of the steels* [a]

Steel	Thickness	Yield point [b]		Tensile strength		Elongation (8 in.)	
		As rolled	Normalized	As rolled	Normalized	As rolled	Normalized
	in.	*lb/in.*²	*lb/in.*²	*lb/in.*²	*lb/in.*²	*Percent*	*Percent*
138	¼	41,700	37,600	62,400	59,900	32.5	34.1
	½	40,800	36,100	61,100	57,900	34.7	36.7
	¾	37,700	42,600	61,300	60,300	33.8	37.0
139	¼	52,800	46,800	73,600	66,600	28.3	25.0
	½	52,800	46,600	73,700	67,800	23.3	32.4
	¾	44,800	45,400	72,100	67,200	35.0	30.5
140	¼	52,200	43,400	78,800	74,400	29.5	46.2
	½	47,500	41,400	73,700	70,400	26.2	30.3
	¾	47,700	42,600	74,900	71,400	--------	32.5
141	¼	46,800	37,900	65,900	60,100	27.8	27.8
	½	51,500	48,100	73,000	68,800	25.0	26.8
	¾	46,800	46,400	73,600	70,100	28.4	29.3

a Tensile-property tests were made at the Physical Laboratory, Model Basin, Washington, D. C.
b Yield point was determined by "drop of the beam" of the testing machine.

TABLE 2.—*Tensile properties of the steels*—Continued

Steel	Thickness	Yield point		Tensile strength		Elongation (8 in.)	
		As rolled	Normalized	As rolled	Normalized	As rolled	Normalized
	in.	*lb/in.²*	*lb/in.²*	*lb/in.²*	*lb/in.²*	*Percent*	*Percent*
143	¼	65,700	45,200	80,200	62,700	18.5	29.1
	½	61,800	45,800	79,000	63,600	20.9	28.4
	¾	58,300	47,300	76,600	65,000	22.5	28.5
144	¼	64,200	49,000	85,900	71,100	22.3	26.0
	½	64,000	----------	82,700	----------	22.0	----------
	¾	60,100	----------	84,400	----------	23.6	----------
145	¼	----------	35,200	81,000	60,000	15.3	27.7
	½	43,500	40,200	65,600	66,400	25.8	23.8
	¾	50,900	44,000	79,700	75,000	24.2	24.6
146	¼	59,000	57,700	71,100	68,500	27.7	28.3
	½	53,300	55,900	68,300	67,700	26.6	28.1
	¾	49,200	50,400	67,000	66,100	27.4	28.5
147	¼	59,900	60,200	75,300	73,600	26.5	28.2
	½	53,900	58,400	72,900	72,500	25.6	27.0
	¾	49,700	57,600	71,600	72,300	26.3	26.5
148	¼	----------	59,900	81,400	80,500	20.4	20.8
	½	57,800	53,800	81,000	77,200	18.1	21.3
	¾	54,500	61,900	82,700	79,600	14.3	19.1
149	¼	59,700	58,600	69,700	73,200	25.2	27.7
	½	58,300	57,000	72,000	71,100	25.0	22.6
	¾	54,700	53,300	70,300	69,600	28.3	28.6
150	¼	62,600	51,400	75,100	69,000	24.0	24.8
	½	51,100	47,700	71,200	68,900	26.5	27.4
	¾	47,300	48,200	72,400	71,500	27.1	28.2
157	¼	75,600	57,800	90,000	62,300	19.6	29.3
	½	61,700	47,000	81,800	64,100	19.4	28.3
	¾	----------	46,600	80,000	65,200	21.3	28.5
161	¼	55,500	----------	72,400	----------	25.6	----------
	½	66,200	----------	71,000	----------	25.9	----------
	¾	62,600	----------	70,200	----------	28.9	----------
163	¼	74,700	63,600	86,300	65,400	18.8	23.4
	½	60,900	41,800	78,600	53,900	20.6	24.3
166	½	50,800	----------	68,600	----------	27.0	----------
168	¼	----------	----------	70,400	68,200	23.8	24.4
	½	60,000	48,000	73,600	66,100	19.2	26.7
201	¼	55,400	51,300	77,800	76,200	24.0	26.0
	½	51,200	54,300	78,100	78,500	29.0	29.0

In the as-rolled condition, steels 139, 143, 144, 147, 149, 150, 161, and 201 complied with all of the tensile property requirements, and in the normalized condition, only steels 147, 148, 149, and 201 met these requirements.

The entire schedule of bend tests was not completed on all of the steels. The results of detailed studies of the nonmetallic inclusions, vacuum-fusion and residue analyses, and microstructural features are presented on eight steels only, 141, 144, 145, 146, 147, 148, 149, and 150. Five of these steels were carried through the entire bend-test schedule. The bend-test schedule was completed also on one plain carbon steel, 139.

Typical microstructures in the unetched condition, showing nonmetallic inclusions are shown in figure 1. The inclusions were of the following types:

Steel No.	*Types of inclusions*
141	Some Al_2O_3, silicates, sulfides. No complex inclusions.
144	Few silicates, numerous sulfides, simple and complex.
145	Few silicates, dark complex oxides, large complex inclusions with acicular structures.
146	Few sulfides, complex oxides.
147	Few sulfides, complex oxides, very few silicates.
148	Many Al_2O_3 inclusions, complex oxides, silicates, sulfides.
149	Few complex oxides, sulfides.
150	Complex inclusions, few silicates.

Steels 141, 144, 145, and 148 were very dirty, while steels 146, 147 149, and 150 were clean.

The amounts of oxygen, nitrogen, and hydrogen in these steels were determined by vacuum-fusion analyses of samples from the ½-in. plates. The results are given in table 3.

TABLE 3.—*Results of vacuum fusion analyses*

Steel	Oxygen	Nitrogen	Hydrogen	Steel	Oxygen	Nitrogen	Hydrogen
	Percent	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*
141	0.012	0.004	None	147	0.005	0.005	0.0002
144	.005	.005	None	148	.037	.005	----------
145	.039	.004	None	149	.005	.004	.0001
146	.005	.005	None	150	.010	.004	None

Steels 145 and 148 were very high in oxygen, and there was more oxygen in steel 141 than is usually found in clean steels. It will be noted by comparing these results with the microstructures that oxygen was highest in the dirty steels, 141, 145, and 148. Steel 144 also contained numerous inclusions, but these were largely sulfides. Most of the inclusions in steel 148 were Al_2O_3, and most of those in 145 were complex oxides, probably mixtures of FeO-MnO. There were some Al_2O_3 and other oxides and silicates in steel 141.

Residue analyses for Al_2O_3 were made on steels having the highest oxygen contents. Results of these analyses are given in table 4.

TABLE 4.—*Results of residue analyses*

Steel	Alumina (residue)	Oxygen as Al_2O_3 (calculated)	Oxygen as other constituents (calculated)
	Percent	*Percent*	*Percent*
141	0.021	0.010	0.002
145	.001	Trace	.039
148	.071	.033	.004

The results of these analyses confirm the microscopic study of the inclusions, in that most of the oxygen in steels 141 and 148 was present as Al_2O_3 while that in steel 145 was in the form of other oxides, probably FeO-MnO.

Typical microstructures of the ½-in. plate metals, as-rolled and after normalizing at 1,650° F for 1 hour, are shown in figures 2 and 3. In

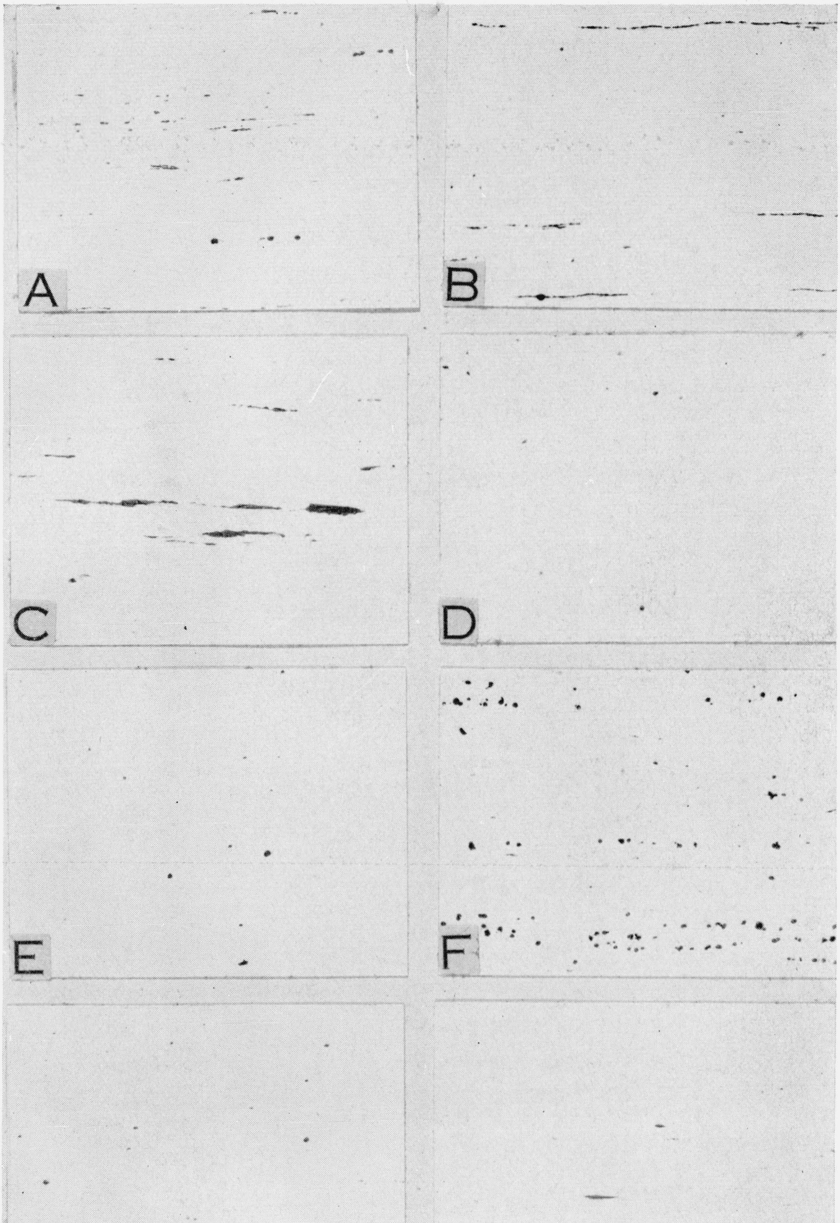


FIGURE 1.—*Nonmetallic inclusions; ½-in. plates; unetched; ×100.*

A, Steel 141, manganese-silicon.
B, Steel 144, manganese-vanadium.
C, Steel 145, manganese-molybdenum.
D, Steel 146, copper-nickel.
E, Steel 147, copper-nickel.
F, Steel 148, copper-nickel-molybdenum.
G, Steel 149, copper-nickel-phosphorus.
H, Steel 150, 2½ percent nickel.

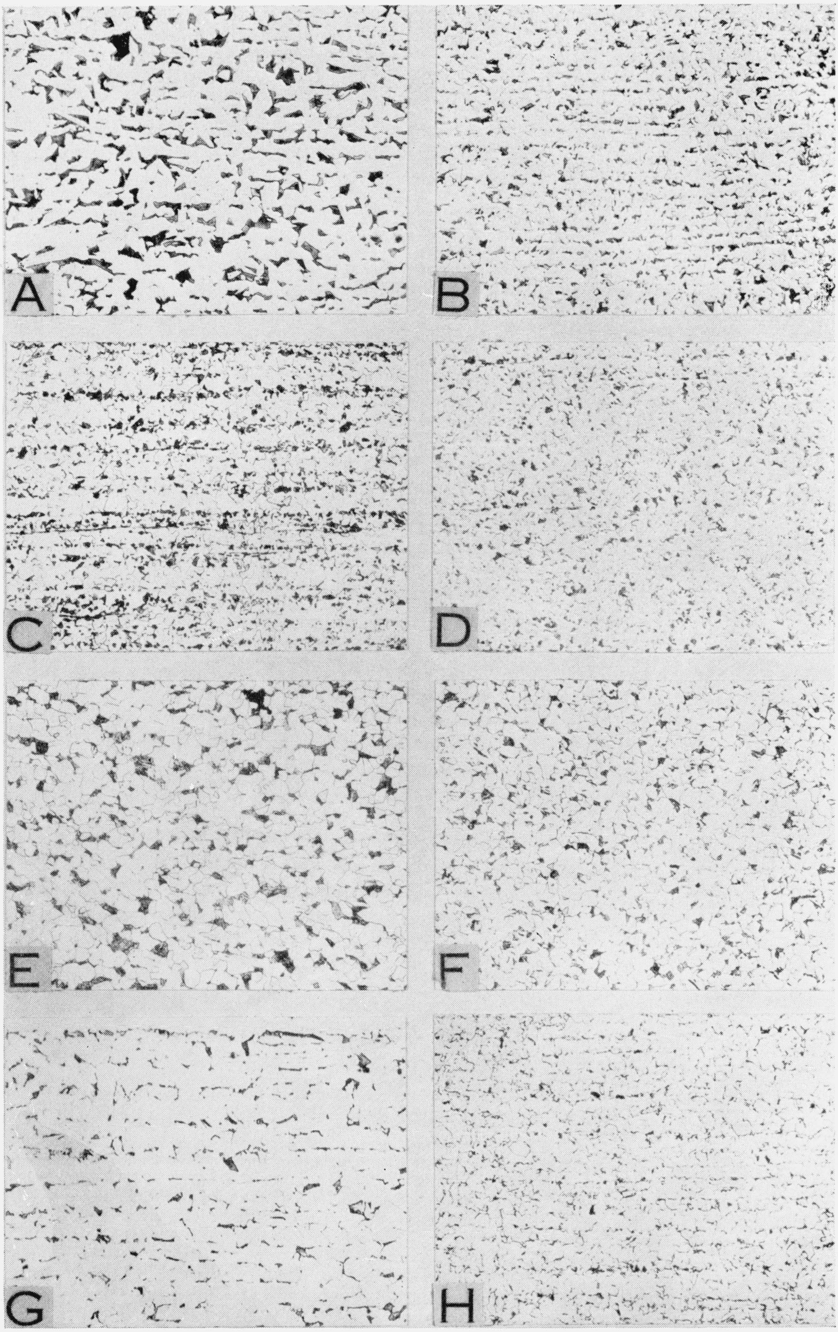


FIGURE 2.—*Typical microstructures; ½-in. plates; etchant, 1 percent nital; ×100.*

A, Steel 141, manganese-silicon, as-rolled.
B, Steel 141, manganese-silicon, normalized.
C, Steel 144, manganese-vanadium, as-rolled.
D, Steel 144, manganese-vanadium, normalized.
E, Steel 145, manganese-molybdenum, as-rolled.
F, Steel 145, manganese-molybdenum, normalized.
G, Steel 146, copper-nickel, as-rolled.
H, Steel 146, copper-nickel, normalized.

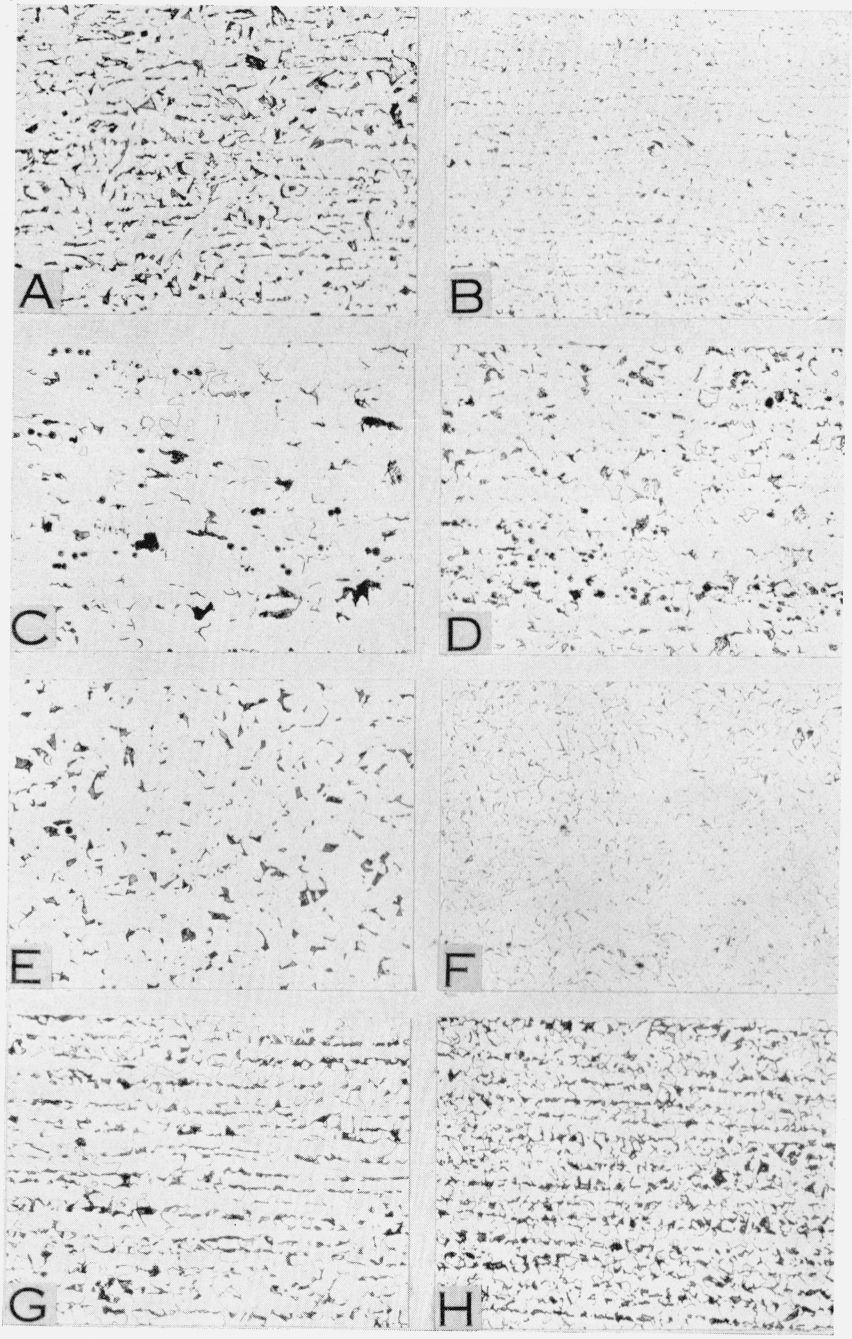


FIGURE 3.—*Typical microstructures; ½-in. plates; etchant, 1 percent nital; ×100.*

A, Steel 147, copper-nickel, as-rolled.
B, Steel 147, copper-nickel, normalized.
C, Steel 148, copper-nickel-molybdenum, as-rolled.
D, Steel 148, copper-nickel-molybdenum, normalized.
E, Steel 149, copper-nickel-phosphorus, as-rolled.
F, Steel 149, copper-nickel-phosphorus, normalized.
G, Steel 150, 2½ percent nickel, as-rolled.
H, Steel 150, 2½ percent nickel, normalized.

the as-rolled condition, steels 141, 144, 146, 147, and 150 contained some banded structure. After normalizing, some banding was found in steels 141, 146, 147, and 150, indicating that chemical segregation was responsible for the banded structure in these steels. However, the banding found in steel 144 had largely disappeared after normalizing, indicating that this steel had been finished "cold" in rolling.

While microstructures from ½-in. plates only are shown in this report, specimens from the ¼- and ¾-in. plates were also examined. In general, in the as-rolled condition, the thinner plates had smaller ferrite grain sizes than the thicker plates, due to the additional working which they received in rolling. After normalizing, the grain sizes for the different thicknesses of plates were more nearly uniform.

The austenitic grain size and grain-coarsening temperature were determined for some of the steels by a gradient-quenching method proposed by Vilella and Bain.[6] Most austenitic grain size studies have been made on specimens carburized at some selected temperature (usually 1,700° F) for 8 hours or more. There have been objections to this procedure due to the high temperature, the long time of heating required, and to the possible introduction of impurities or foreign material, which might have a significant effect on the grain size of a steel. In the gradient-quenching method about ½ in. of the length of the specimen (1½ in. long by ¼ in. wide by the full plate thickness) was quenched from a desired temperature into a brine solution. The remainder of the length was allowed to cool in air above the brine.

The quenched end was composed of martensite and the air-cooled end of pearlite. At some point in the quenched end of the specimen, the critical cooling rate for the steel was exceeded and fine pearlite was formed around the austenitic grains, outlining them with black envelopes. In the air-cooled end, the grains were outlined by proeutectoid ferrite. This method was considered to be much faster than the carburizing method and did not introduce unknown variables into the steel.

Specimens of all plate thicknesses and in both as-rolled and normalized conditions were heated to temperatures ranging from 1,300° to 2,400° F, held 10 minutes, and gradient-quenched. There was no difference in grain size at any given temperature in the as-rolled and the normalized plates. Normalizing, therefore, apparently did not affect the grain size nor the grain-growth temperature.

Austenitic grain sizes of the ½-in. plates of some of the steels at various temperatures above the critical ranges of the steels are given in table 5. The grain-size designations are in accordance with those of the American Society for Testing Materials Specification E–19–39T.

TABLE 5.—*Austenitic grain size numbers of steels at various temperatures*

Steel	Temperature, °F.				Steel	Temperature, °F.			
	1,600	1,700	1,800	1,900		1,600	1,700	1,800	1,900
138	6	6	5	2	146	8	8	7, 8	[a] 3 and 7
139	7	7	7	7	147	8	8	8	2
140	6	5	2	1	148	6	5	4	3
141	8	7	7	7	149	7	7	7	7
144	8	8	[a] 4 and 6	[a] 3 and 6	150	7	[a] 5 and 7	[a] 3 and 7	[a] 2 and 7
145	------	6	5	3					

[a] Mixed.

[6] J. R. Vilella and E. C. Bain, *Revealing the austenitic grain size of steel*, Metal Progress **30**, 39 (1936).

Three steels, 139, 141, and 149, resisted grain growth up to 1,900° F and had fine grains at this temperature. In steels 146 and 147 there was grain growth at 1,900° F, in steels 138 and 144 at 1,800° F, while in steels 140, 145, 148, and 150 the grain size apparently started to increase at the top of the transformation range and continued increasing to the highest temperature. Steel 145 was not completely austenitic at 1,600° F; some proeutectoid ferrite still existed at this temperature. Steels 144, 146, and 150 had mixed grain sizes, that is, while some grains showed growth at higher temperatures, some of the small grains did persist at those temperatures.

In general, the steels which had the highest coarsening temperature were those which did not contain appreciable amounts of carbide-forming elements. Those steels which coarsened at low temperatures, for the most part, did contain carbide-forming materials, particularly molybdenum. Three low-alloy steels, all of which contained molybdenum, and one plain carbon steel started to coarsen at the top of the critical range. One other molybdenum-containing steel did not coarsen at 1,900° F.

All of the steels which coarsened at low temperatures contained more than normal amounts of oxygen. Two of these steels, 145 and 148, contained abnormally high oxygen.

Most of the steels which coarsened at the highest temperatures contained copper and nickel in appreciable quantities. Two steels, 141 and 139, contained only small amounts of these elements.

McQuaid-Ehn grain-size tests were made in accordance with American Society for Testing Materials Specification E–19–39T. Specimens were packed in solid carburizer and heated at 1,700° F for 16 hours, then cooled in the furnace to 900° F to permit the rejection of cementite to the grain boundaries in the hypereutectoid zone.

Grain size numbers for the ½-in. plates are given in table 6. These include both the numbers after gradient-quenching and after carburizing for 16 hours at 1,700° F.

TABLE 6.—*Grain-size numbers at 1,700° F*

Steel	After carburizing	After gradient-quenching	Steel	After carburizing	After gradient-quenching
138	2	6	146	8	8
139	7	7	147	8	8
140	2	5	148	2	5
141	7	7	149	7	7
144	7	8	150	4	[a] 4 and 7
145	3	6			

[a] Mixed.

There was considerable difference in grain size after the two treatments. Those steels which after gradient-quenching had a small grain size generally had the same approximate size in the carburizing test. However, steels which had an intermediate size after quenching had larger size grains in the McQuaid-Ehn test. This is due most likely to the length of time at a given temperature and possibly to the introduction of carbon into the material during the test, thus changing some of the properties of the material.

In the ½-in. plates, steels 138, 140, 145, 148, and 150 had normal structures, steels 139 and 149 slightly abnormal, steels 141, 146, and 147 abnormal, and steel 144 very abnormal.

Comparing the two tests, it is found that, in general, the abnormal steels had the highest coarsening temperatures and those with normal structures had the lowest coarsening temperatures.

Chemical analyses and tensile-property tests indicated that not all sizes of plates from some steels were from the same heat. This was confirmed by the results of the carburizing tests. Steel 141, in the ¼-in. thickness, had a normal structure with large grains, while the ½- and ¾-in. plates had abnormal structures and small grains. Steel 149, likewise, had different grain sizes, the specimen from the ¼-in. plates having small grains and abnormal structures, while those from the ½- and ¾-in. plates had larger grains and normal structures. Steel 150 had a composite structure in the ¼-in. plate, in which the edge had large grains and normal structure while the interior was abnormal with small grains.

III. METHOD OF TEST

1. GUIDED BEND TESTS

(a) PREPARATION OF SPECIMENS

Specimens from each thickness of plate, in both the as-rolled and the normalized conditions, were prepared as shown in figure 4. A 12- by 24-in. piece of the plate was cut with the short dimension parallel to the direction of rolling. A piece 4 by 24 in. of the same material was attached to this plate by means of double-fillet welds with the length of the welds perpendicular to the direction of rolling. The welds were continuous and made in one pass. One fillet was made and the specimen allowed to return to the original plate temperature before the second fillet was welded in the same direction as the first, that is, started from the same end.

All welds were made by the same operator, using direct current, reversed polarity, and organic-covered electrodes from the same source. Electrode sizes and current conditions for the three plate thickness were as follows:

Plate thickness	Electrode size	Welding current	Arc voltage
in.	*in.*	*Amperes*	*Volts*
¼	⅛	100 to 105	26 to 28
½	5/32	130 to 135	26 to 28
¾	3/16	160 to 170	26 to 28

Very close tolerances were maintained, and any specimens showing undercutting, improper weld size, or visible welding defects were discarded.

All the steels were welded when the plates were at room temperature. To simulate the conditions of welding in cold weather, additional plates were cooled to temperatures of 10°, 0°, −10°, and −20° F, and welding was started when the plates were at these temperatures.

Four specimens for the bend test and one specimen for examination of the microstructure and hardness tests were sawed from each assembly, as shown in figure 4. There was no further edge preparation nor were the welds machined in any manner.

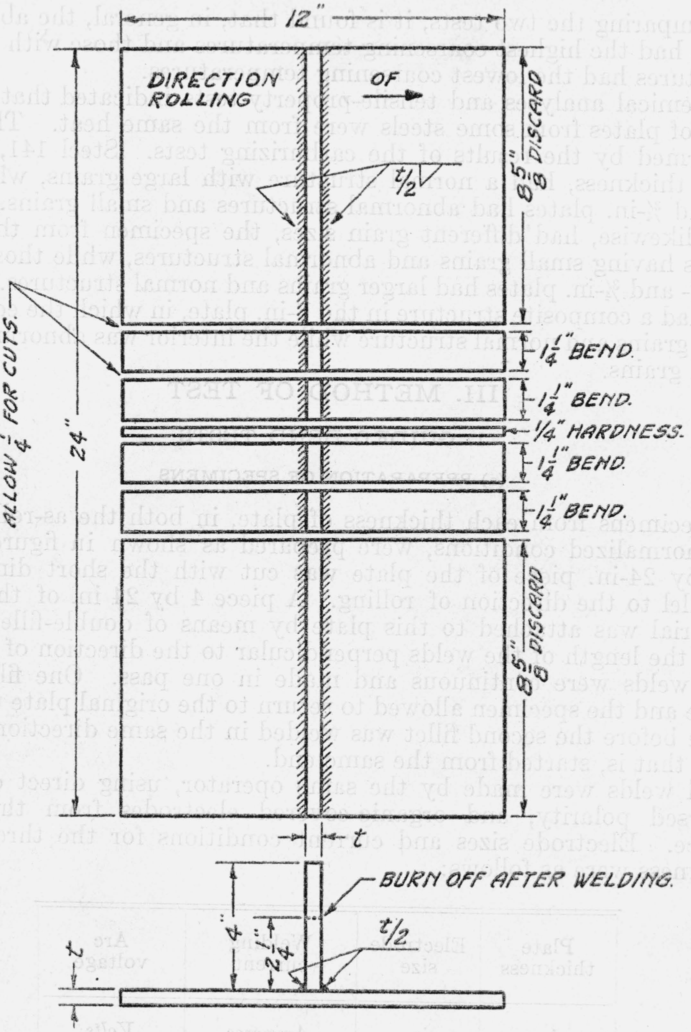


FIGURE 4.—*Plate layout and location of test specimens.*

(b) BENDING APPARATUS

A bending jig similar to that shown in figure 5 was designed for each thickness of plate. The specimen was supported on hardened steel cylinders, and the tongue of the T was wedged firmly in the guide, which moved freely in vertical ways. The specimen was loaded at the center on the face opposite to the T, through a plunger having a semi-cylindrical end of the same radius as the supporting cylinders. As the tongue of the specimen was constrained by the guide to move in a vertical plane, bending was forced to take place uniformly at the toe of each fillet. The deflection was measured on a scale attached to the plunger. The angle of bend (the supplement of the internal angle between the legs of the specimen) was obtained from a curve showing

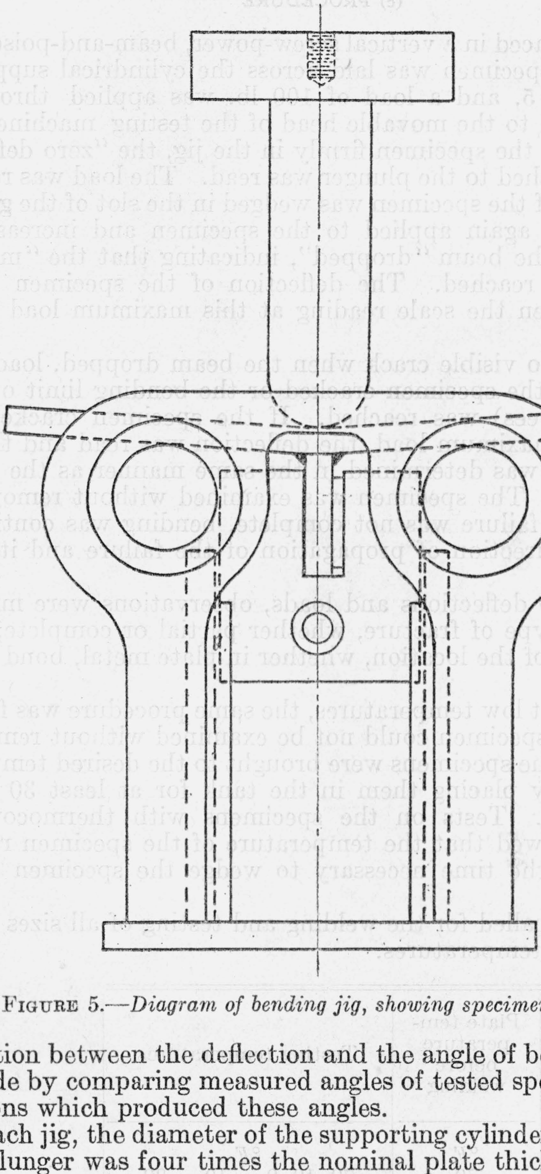


FIGURE 5.—*Diagram of bending jig, showing specimen in place.*

the relation between the deflection and the angle of bend. This curve was made by comparing measured angles of tested specimens with the deflections which produced these angles.

For each jig, the diameter of the supporting cylinders and of the end of the plunger was four times the nominal plate thickness, *t*, and the distance between centers of the supporting cylinders was 12*t*. The jigs are shown in figure 6.

To observe the effects of low temperatures on the bending properties, bend tests were made at temperatures from +10° F to −20° F. For testing specimens at low temperatures, the jig was placed in an insulated tank containing a solution of ethylene glycol (50 percent by volume) in water. The liquid covered the specimen when in position in the jig and was cooled to the desired temperature by adding dry ice (CO_2).

(c) PROCEDURE

The jig was placed in a vertical screw-power, beam-and-poise testing machine. The specimen was laid across the cylindrical supports, as shown in figure 5, and a load of 100 lb. was applied through the plunger attached to the movable head of the testing machine. With this load seating the specimen firmly in the jig, the "zero deflection" of the scale attached to the plunger was read. The load was removed, and the tongue of the specimen was wedged in the slot of the guide.

The load was again applied to the specimen and increased continuously until the beam "dropped", indicating that the "maximum load" had been reached. The deflection of the specimen was the difference between the scale reading at this maximum load and the zero deflection.

If there was no visible crack when the beam dropped, loading was continued until the specimen cracked or the bending limit of the jig (about 120 degrees) was reached. If the specimen cracked either before or after maximum load, the deflection was read and the angle at initial failure was determined in the same manner as the angle at maximum load. The specimen was examined without removing the load, and if the failure was not complete, bending was continued to determine the direction of propagation of the failure and its extent at jig capacity.

In addition to deflections and loads, observations were made also of the kind or type of fracture, whether partial or complete, sudden or gradual, and of the location, whether in plate metal, bond zone, or weld metal.

For the tests at low temperatures, the same procedure was followed, except that the specimen could not be examined without removing it from the jig. The specimens were brought to the desired temperature before testing by placing them in the tank for at least 30 minutes prior to testing. Tests on the specimens with thermocouples in drilled holes showed that the temperature of the specimen rose only slightly during the time necessary to wedge the specimen into the guide.

The program called for the welding and testing of all sizes of steels at the following temperatures.

Plate temperature before welding	Testing temperatures
°*F*	°*F*
70	70, 10, 0, −10, −20
10	70
0	70, 10, 0, −10, −20
−10	70
−20	70, 10, 0, −10, −20

With four specimens to be tested under each condition, a total of 408 bend tests was required for the complete investigation of each steel. As the work continued, it was evident that some steels were unsatisfactory, and further tests were discontinued in order to shorten

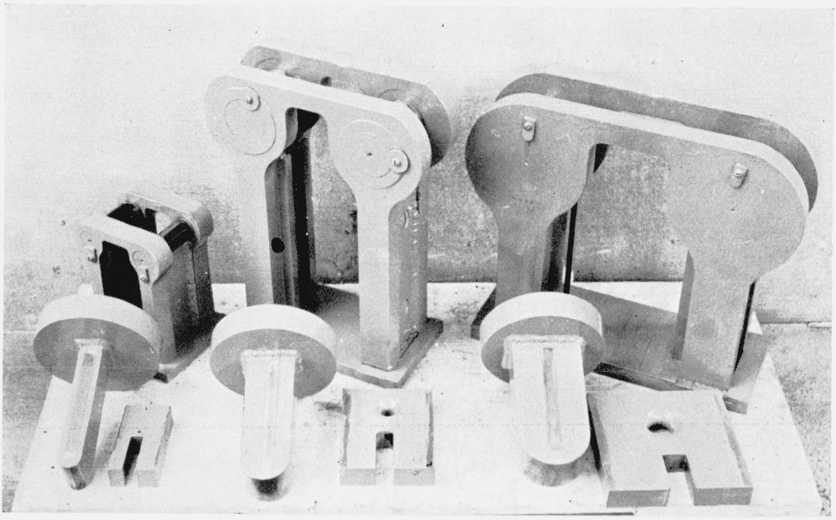
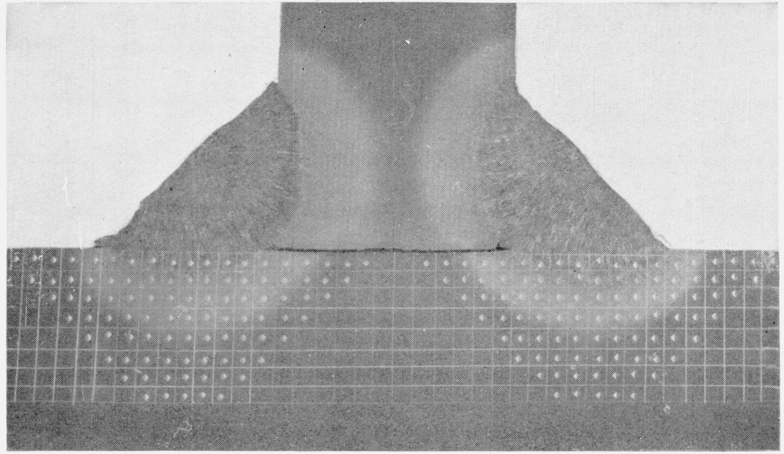


FIGURE 6.—*Photograph of bending jigs used for ¼-, ½-, and ¾-in. specimens, showing all essential parts of each jig.*



164	162	161	164	174	196	188	162	163	161	158	162	193	180	172	171	169	163	163
	163	164	161	172	175	185	198	200	206	208	191	182	172	176	166	162	164	
		161	158	162	168	168	170	173	171	169	167	168	170	165	161	157		
			162	158	159	160	166	165	164	164	165	160	162	157	155			
				163	157	159	161	162	162	161	158	158	156	154				
					163	160	160	162	160	155	156	159	156					
						164	159	161	160	160	160	160						
							159	162	161	160	160							

163	161	165	169	178	211	178	167	167	172	176	170	201	181	173	166	166	168	171
	165	163	168	171	185	192	208	191	199	219	204	188	174	174	166	167	166	
		160	162	168	167	170	174	178	178	179	171	176	170	166	165	165		
			164	163	164	164	167	168	168	172	169	166	160	159	160			
				162	160	166	166	165	165	167	164	163	162	166				
					163	158	163	161	165	164	160	163	161					
						163	161	163	164	167	165	163						
							167	162	164	161	158							

FIGURE 7.—*Location of Vickers indentations on specimens and hardness numbers corresponding to the indentations*

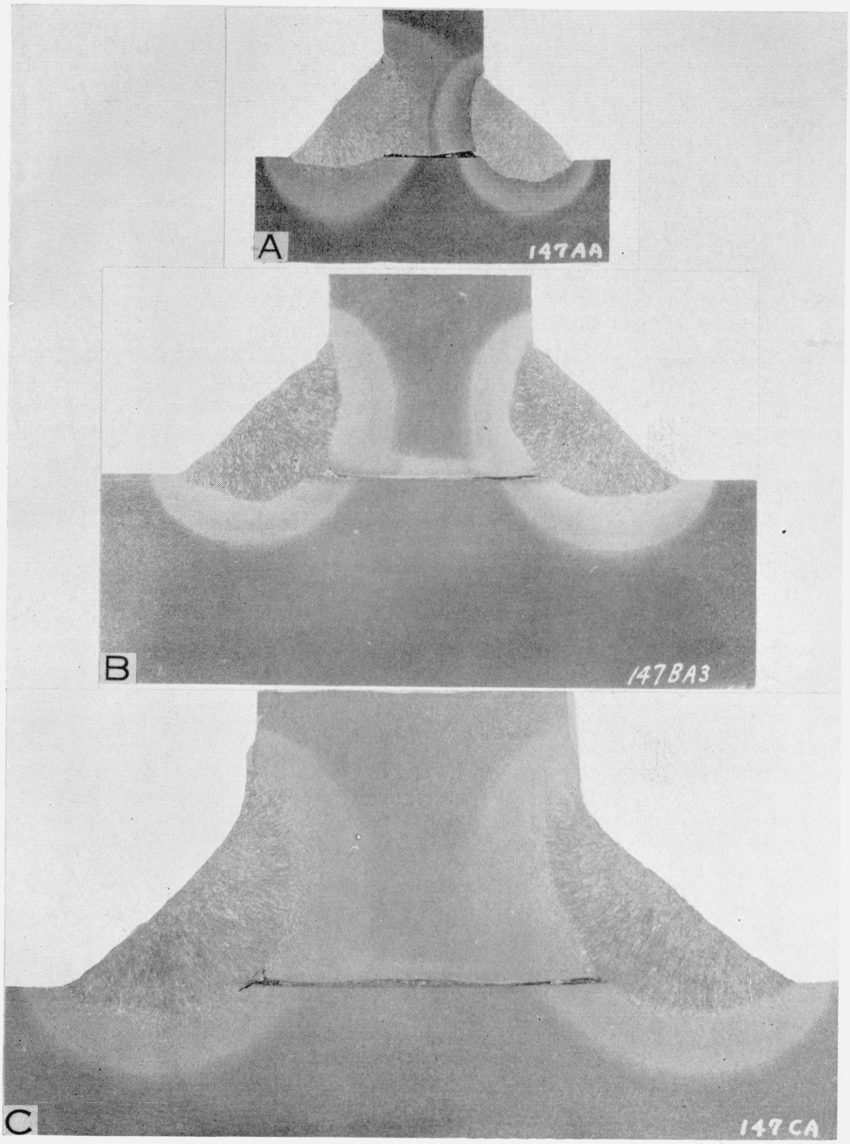


FIGURE 8.—*Typical macrostructures of the welded specimens.*

A, ¼-in. plate; *B*, ½-in. plate; *C*, ¾-in. plate.

the program. The complete program of tests was carried out on only 6 of the 18 steels (Nos. 139, 144, 146, 147, 149, and 150).

2. HARDNESS TESTS

One specimen for each composition, thickness, and condition of steel was ruled in millimeters, as shown in figure 7, and Vickers numbers were obtained for each square in the heat-affected zone.

Results for the six completely tested steels are given in table 7, showing the hardness of the plate metal before and after welding.

TABLE 7.—*Effect of welding on hardness of plate metals*

Steel	Plate thickness	Original plate		After welding highest value		Increase of hardness	
		As-rolled	Normalized	As-rolled	Normalized	As-rolled	Normalized
	In.	*Vickers No.*	*Vickers No.*	*Vickers No.*	*Vickers No.*	*Vickers No.*	*Vickers No.*
139	1/4	153	145	215	194	62	49
	1/2	149	144	219	214	70	70
	3/4	149	145	194	192	45	47
144	1/4	177	154	247	230	70	76
	1/2	150	159	252	231	102	72
	3/4	182	152	242	227	60	75
146	1/4	156	155	185	190	29	35
	1/2	150	150	198	200	48	50
	3/4	154	149	206	200	52	51
147	1/4	164	164	251	240	87	76
	1/2	164	158	238	271	74	113
	3/4	171	157	223	214	52	57
149	1/4	165	160	208	198	43	38
	1/2	158	156	195	193	37	37
	3/4	153	152	197	188	44	36
150	1/4	168	158	224	223	56	65
	1/2	152	150	209	229	57	79
	3/4	155	157	208	225	53	68

The highest hardness (182) of the as-rolled plates was found in the ¾-in. plate of steel 144 and the lowest (149) in the ½- and ¾-in. plates of steel 139. The ½-in. plate of steel 144 also had a low value (150). After welding, the highest hardness was found in the ½-in. plate of steel 144 (252), an increase of 102 Vickers numbers.

The highest hardness of the normalized plates (164) was found in the ¼-in. plate of steel 147. The hardest point after welding was 271, found in the ½-in. plate of steel 147. This plate also had the greatest increase in Vickers numbers (113) as a result of welding.

None of the specimens hardened excessively, and the ranges of hardness were comparatively narrow.

3. MACROSTRUCTURES

Specimens from the six completely tested steels were polished, etched, and examined both macroscopically and microscopically. A typical macrophotograph is shown in figure 8. The results of these studies showed that all welds were of proper contour and size, that heat penetration was normal for the plate and electrode size used, and that there were no serious defects in the plate or weld metals.

Microstructures of welded specimens showed that, with the exception of steel 147, the grains at the fusion boundary were not excessively large. There were no sharp boundary lines, and the plate metals for the most part diffused gradually into weld metals. Likewise the changes in structure in the transition zones of the plate metals were very gradual.

IV. RESULTS

1. MAXIMUM LOAD

For the specimens in which no fracture occurred the load increased, with increase in angle of bend, to a maximum and then decreased continuously without any increase, until the limit of the jig was reached. Usually the maximum load occurred after the specimen had bent 60°. The agreement between duplicate specimens, as to both maximum load and angle, was generally very close.

Specimens from some of the steels cracked audibly or visibly while the load was still increasing and at bend angles usually much less than 60°. In such cases the results of duplicate specimens did not agree, either in load or angle at which cracking occurred. For specimens from other steels, cracking did not occur until after the maximum load had been attained and the load was decreasing. When this occurred, there also was lack of agreement among duplicate specimens for the load at which cracking occurred, although the agreement on maximum load and angle at maximum load was close.

Because the maximum load on a specimen was affected directly by changes in dimensions that were indeterminate on these specimens and could not be reduced to stress values, this maximum load in the bend test was not considered an important basis of comparison. It was even more difficult to determine exactly the load, and particularly the angle at which cracking began, and no attempt was made to use these as a basis of comparison. The maximum load, with or without failure by cracking, was indicated by a drop of the beam of the testing machine similar to that at the maximum load in a tensile test of a ductile metal. The angle of bend at this load was readily determined, and also whether the failure occurred before or after the maximum load had been passed. All failures were in one or the other category, and those which appeared to coincide with the maximum load were considered to have occurred under an increasing load.

Although it would not be advisable to recommend minimum numerical values for maximum load and angle of bend, alone, as a basis for acceptable welding quality, it was considered that the higher these values the greater were the indicated strength and ductility of the joint. These values were considered useful for comparisons of specimens of different steels welded and tested under the same conditions. The use of values for angle of bend at maximum load is discussed in the following section.

The average values of maximum loads are given in table 8. In this and other tables where data are incomplete, the value is followed by a small "x." Since the maximum load is apparently not a simple function of plate thickness, the values for the various plate sizes cannot be directly compared; but the rank numbers, which are based

Table 8 . - MAXIMUM LOADS. (Average of 4 Specimens.)

Steel No. & Cond.	Test Temp. °F	1/4"					Rank	1/2"					Rank	3/4"					Rank	All Sizes Combined		Steel No. & Cond.
		Weld Temperature, °F						Weld Temperature, °F						Weld Temperature, °F						70°F	All Temp.	
		70	10	0	-10	-20		70	10	0	-10	-20		70	10	0	-10	-20		Ave. Rank	Ave. Rank	
139 AR	70	3755	3560	3460	3780	3770	1	5810	6050	5850	5620	5600	0	9450	9390	9160	9160	9250	3	1.3		139 AR
	10	3960		3710		3960		6540		6610		6840		10200		10290		9960				
	0	3960		3850		3990		6800		6620		6790		10220		10260		9800				
	-10	4050		3880		3990		6500		6690		6410		10410		10080		10040				
	-20	4030		3780		4070		7040		6900		6580		10140		10180		9940				
	Ave.	All Temperatures				3860	2					6430	2					9880	5		3.0	
139 N	70	3687	3620	3700	3660	3700	1	6162	5550	5120	4840	4700	1	9088	9070	9440	9280	8950	1	1.0		139 N
	10	3840		3740		3910		6860		6850		7120		9640		9610		9740				
	0	3870		3900		4000		6860		6920		6950		9540		9910		9900				
	-10	3980		3960		3960		7010		6700		6880		9760		9550		9750				
	-20	3980		3940		3910		7040		6780		6890		9890		9600		10100				
	Ave.	All Temperatures				3840	2					6430	2					9580	3		2.3	
144 AR	70	5100	5420	5350	5180	5000	8	7570	7748	7675	8055	7820	6	10210	10300	10380	10580	10475	7	7.0		144 AR
	10	5490		5620		5260		8181		8344		8049		10780		10800		10820				
	0	5590		5490		5350		8355		8484		8005		10510		10800		10700				
	-10	5780		5360		5250		8320		8221		8141		10720		10830		10960				
	-20	5740		5280		5570		8316		8566		8261		10680		10670		10950				
	Ave.	All Temperatures				5400	10					8120	8					10660	9		9.0	
144 N	70	4685	4450	4900	4630	4590	6	7655	7220	7362	7615	7145	6	8962	8900	8800	9020	9125	0	4.0		144 N
	10	4700		4600		4730		7845		7870		7929		9420		9400		9130				
	0	4460		4790		4880		7786		7595		7738		9260		9140		9175				
	-10	4660		4680		4470		7860		7870		7640		9360		9080		9410				
	-20	4700		4750		4760		8108		7940		7716		9626		9382		9808				
	Ave.	All Temperatures.				4670	6					7700	6					9230	2		4.7	
146 AR	70	3968	--	4010	4120	4160	2	6962	6925	6888	6988	7038	4	10300	10000	9950	10140	10160	7	4.3		146 AR
	10	4170		4335		4160		7670		7500		7388		11000		10760		10690				
	0	4340		4380		4260		7638		7425		7488		11290		11390		10575				
	-10	4315		4170		4050		7775		7588		7525		10790		10750		10925				
	-20	4280		4300		4290		7838		7733		7562		11250		11150		10690				
	Ave.	All Temperatures				4210	4					7410	5					10690	9		6.0	
146 N	70	3603	3730	3590	3760	3600	0	6825	6838	6912	6912	6925	3	9738	9890	9800	9890	9850	4	2.3		146 N
	10	3980		3950		3630		7425		7160		7500		10390		10420		10500				
	0	3828		3770		3950		7475		7288		7425		10600		10740		10490				
	-10	4050		3900		3930		7462		7062		7475		10300		10500		10580				
	-20	4140		4060		3810		7562		7500		7581		10320		10560		10690				
	Ave.	All Temperatures				3840	2					7250	5					10310	7		4.7	
147 AR.	70	4051	4220	4325	4320	4530	3	7150	7188	7213	7460	7512	4	10600	10450	10910	10660	10860	9	5.3		147 AR
	10	4390		4460		4500		8038		7850		7788		11450		11120		11090				
	0	4350		4475		4525		8062		7850		7838		11550		11250		11490				
	-10	4360		4690		4500		8488		8200		7650		11600		10425		11550				
	-20	4570		4600		4475		8250		7950		7975		11990		11260		11275				
	Ave.	All Temperatures				4430	5					7790	6					11150	10		7.0	
147 N	70	3808	3870	3862	3958	4068	2	7288	7100	7000	7350	7392	5	10050	9950	8960	10250	10210	6	4.3		147 N
	10	4118		3692		4255		7612		7750		7688		11100		10710		10910				
	0	4098		4222		4185		7662		7650		7750		11140		10775		10930				
	-10	4095		4135		4100		7725		7825		7675		10940		11050		11025				
	-20	4262		4218		4245		7588		7762		7688		11580		11040		10900				
	Ave.	All Temperatures				4070	3					7560	6					10680	9		6.0	
149 AR	70	4745	4766	4542	4397	4486	6	7062	7594	7095	7591	7222	4	10100	10370	10385	10370	10440	6	5.3		149 AR
	10	5040		4710		4400		7264		7729		7638		10475		10705		10490				
	0	--		4570		4340		7462		7671		7744		10270		10410		10205				
	-10	--		4680		4520		7371		7608		7496		10420		10460		10230				
	-20	--		4840		4660		7550		7505		7728		10340		10930		10550				
	Ave.	All Temperatures				4620x	6					7490	5					10420	8		6.3	
149 N	70	4360	4710	4670	4508	4585	4	6750	6895	6939	7270	7195	3	10050	10250	10140	9840	10060	6	4.3		149 N
	10	--		4890		4670		7081		7295		7701		10250		10740		10130				
	0	--		4820		4390		7144		7266		7641		10060		10390		10310				
	-10	--		4630		4550		7291		7382		7450		10100		10128		10230				
	-20	--		4760		4370		7236		7385		7462		10320		10320		10440				
	Ave.	All Temperatures				4610x	6					7260	5					10230	7		6.0	
150 AR	70	4345	4510	4270	4530	4510	4	7850	7458	7677	7632	7542	7	8975	9640	9500	9390	9320	0	3.7		150 AR
	10	4710		4090		4980		8184		8230		8344		9490		9360		9700				
	0	4440		4750		4720		8021		8134		8284		9360		9630		9540				
	-10	4390		4740		4550		8004		7906		8166		9370		9450		9650				
	-20	4450		4720		4610		7896		7784		8106		9860		9480		9840				
	Ave.	All Temperatures				4550	5					7950	7					9500	3		5.0	
150 N	70	3860	3680	3650	3670	3242	2	7112	6768	6855	6812	7052	4	8962	9150	9250	9040	8800	0	2.0		150 N
	10	4170		4060		4180		7474		7466		7015		9270		9140		9070				
	0	4300		4120		3680		7502		7540		7725		9080		9090		9172				
	-10	3740		3880		3700		7514		7522		7630		9210		9290		9330				
	-20	3701		3770		3830		7495		7469		7076		9420		9140		9510				
	Ave.	All Temperatures				3840	2					7300	5					9170	1		2.7	

Determination of Rank

Range Subdivisions	1/4"	Under 3609	3610-3799	3800-3999	4000-4199	4200-4399	4400-4599	4600-4799	4800-4999	5000-5199	5200-5399	5400 & over
	1/2"	Under 5999	6000-6299	6300-6599	6600-6899	6900-7199	7200-7499	7500-7799	7800-8099	8100-8399	8400-8699	8700 & over
	3/4"	Under 8999	9000-9199	9200-9399	9400-9599	9600-9799	9800-9999	10000-10199	10200-10399	10400-10599	10600-10799	10800 & over
Rank Numbers		0	1	2	3	4	5	6	7	8	9	10

Table 10. - DEVIATIONS BELOW 60° OF INDIVIDUAL ANGLES.

Steel No. & Cond.	Test Temp. °F	1/4"							1/2"						
		Weld Temperature, °F					Rating	Rank	Weld Temperature, °F					Rating	Rank
		70°	10°	0°	-10°	-20°			70°	10°	0°	-10°	-20°		
139 AR	70	--	26/2	21	0/2	3/3	--	--	0/3	4/1	6/2	5/2	1/2	0x	10
	10	0		26		1			19		36		0		
	0	0		0		9			16		23		9		
	-10	0		8		18			68		48		38		
	-20	3		45		26			33		37		63		
	Total	All Temperatures				186/59	316x	6					406/58	700x	3
139 N	70	0	0	0	0	0	0	10	0	0/2	0/2	0/2	9/2	0	10
	10	0		3		0			9		0		3		
	0	0		0		0			12		3		11		
	-10	0		0		0			8		40		0		
	-20	0		0		0			37		17		5		
	Total	All Temperatures				3/68	4	9					154/60	257x	7
144 AR	70	1	28	50	11	23	25	9	20	24	17	4	14	500	5
	10	43		48		32			15		2		6		
	0	32		60		52			0		4		4		
	-10	28		34		19			2		6		1		
	-20	30		37		38			10		0		8		
	Total	All Temperatures				566/68	832	1					137/68	202	7
144 N	70	0	0	0	0	0	0	10	0	5	0	1	0	0	10
	10	0		1		16			2		0		0		
	0	1		8		35			0		0		0		
	-10	3		6		28			0		0		0		
	-20	19		0		0			0		0		19		
	Total	All Temperatures				117/68	172	8					27/68	40	9
146 AR	70	0	-	0	0	0	0	10	0	0	0	0	0	0	10
	10	0		0		0			0		0		0		
	0	0		0		0			0		9		5		
	-10	3		15		0			0		0		2		
	-20	0		0		0			0		0		9		
	Total	All Temperatures				18/64	28	9					25/68	37	9
146 N	70	20	0	0	0	0	500	5	0	0	0	0	0	0	10
	10	0		0		5			0		0		0		
	0	0		0		0			0		0		2		
	-10	0		0		0			0		28		0		
	-20	0		0		0			5		0		0		
	Total	All Temperatures				25/68	37	9					35/68	52	9
147 AR	70	2	0	2	1	0	50	9	0	19	12	3	8	0	10
	10	0		3		3			0		0		0		
	0	3		0		0			0		0		0		
	-10	8		3		0			1		11		16		
	-20	8		0		1			0		2		19		
	Total	All Temperatures				34/68	50	9					91/68	134	8
147 N	70	8	0	0	0	0	200	8	0	0	0	0	0	0	10
	10	4		9		1			0		0		0		
	0	0		0		0			0		0		0		
	-10	0		0		2			0		0		0		
	-20	0		0		0			16		0		0		
	Total	All Temperatures				24/68	35	9					16/68	24	9
149 AR	70	6	0	13	15	15	150	8	0	2	1	0	0	0	10
	10	2		7		48			0		23		19		
	0	–		3		9			2		0		0		
	-10	–		2		3			0		15		42		
	-20	–		20		16			0		23		7		
	Total	All Temperatures				159/56	284x	7					134/68	197	8
149 N	70	0	3	0	9	0	0	10	0	0	1	0	0	0	10
	10	–		0		8			0		0		20		
	0	–		1		35			5		10		16		
	-10	–		30		12			4		16		27		
	-20	–		55		77			0		31		12		
	Total	All Temperatures				230/52	442x	5					142/68	209	7
150 AR	70	7	18	41	26	7	175	8	0	7	1	15	29	0	10
	10	5		78		0			0		0		0		
	0	28		0		1			7		8		6		
	-10	22		6		14			15		8		12		
	-20	28		14		16			16		12		6		
	Total	All Temperatures				311/68	457	5					142/68	209	7
150 N	70	0	24	20	3	42	0	10	0	1	0	2	0	0	10
	10	0		0		0			0		0		47		
	0	0		4		5			0		0		0		
	-10	2		5		6			0		0		0		
	-20	6		21		4			11		0		71		
	Total	All Temperatures				142/68	209	7					132/68	194	8

Test Temp. °F	3/4"							All Sizes Combined						Steel No. & Cond.
	Weld Temperature, °F					Rating	Rank	W & T at 70°F			W & T All Temp.			
	70°	10°	0°	-10°	-20°			Total	Rating	Rank	Total	Rating	Rank	
70	0	0/1	0/1	0/1	0	0	10	0/7	0x	10				139 AR
10	0		0		0									
0	0		0		10									
-10	0		37		0									
-20	14		7		8									
Total					76/59	129x	8				668/176	380x	6	
70	0	0/3	0	0	0	0	10	0/12	0	10				139 N
10	0		0		0									
0	0		7		0									
-10	0		33		30									
-20	0		34		2									
Total					106/67	158	8				263/195	135	8	
70	37	39	46	46	37	925	0	58/12	483	5				144 AR
10	11		5		4									
0	6		17		6									
-10	21		12		17									
-20	11		48		22									
Total					385/68	567	4				1088/204	533	4	
70	1	9	9	7	0	25	9	1/12	8	9				144 N
10	0		0		0									
0	1		5		0									
-10	17		11		3									
-20	0		2		10									
Total					75/68	110	8				219/204	107	8	
70	0	0	0	0	1	0	10	0/12	0	10				146 AR
10	0		1		0									
0	0		0		5									
-10	0		0		2									
-20	0		0		0									
Total					9/68	13	9				52/200	26	9	
70	0	0	0	0	0	0	10	20/12	167	8				146 N
10	0		0		0/2									
0	0		0		0									
-10	0		0		0									
-20	10		1		0									
Total					11/66	17	9				71/202	35	9	
70	0	6	0	0	0	0	10	2/12	17	9				147 AR
10	6		0		1									
0	0		1		0									
-10	0		36		26									
-20	0		25		44									
Total					145/68	213	7				270/204	132	8	
70	0	0	3	0	0	0	10	8/12	67	9				147 N
10	12		0		0									
0	0		10		0									
-10	2		0		0									
-20	9/3		0		11									
Total					47/67	70	9				87/203	43	9	
70	0	0	9	0	0	0	10	6/12	50	9				149 AR
10	3		0		27									
0	10		0		35									
-10	3		16		20									
-20	32		24		19									
Total					198/68	291	7				491/192	256	7	
70	0	0	2	2	0	0	10	0/12	0	10				149 N
10	0		0		30									
0	2		0		0									
-10	5		9		31									
-20	15		22		13									
Total					131/68	193	8				503/188	268	7	
70	40	0	0	0	0	1000	0	47/12	392	6				150 AR
10	0		25		2									
0	2		24		3									
-10	37		5		14									
-20	44		29		11									
Total					236/68	347	6				689/204	338	6	
70	0	0	0	0	0	0	10	0/12	0	10				150 N
10	0		1		9									
0	2		2		11									
-10	6		9		12									
-20	21		2		0									
Total					75/68	110	8				349/204	171	8	

Determination of Rank

Range Subdivisions	0	1-100	101-200	201-300	301-400	401-500	501-600	601-700	701-800	801-900	901 and over	Range Subdivisions
Rank Numbers	10	9	8	7	6	5	4	3	2	1	0	Rank Numbers

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Table 13. -SUMMARY OF ALL FAILURES.

Steel No.	Failures	Welded and Tested at All Temperatures																W & T at 70°F				Steel No.
		1/4"				1/2"				3/4"				All Sizes Combined				All Sizes Combined				
		AR		N		AR		N		AR		N		AR		N		AR		N		
		%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	
139	Plate	98	0	46	5	96	0	74	2	57	4	53	4	84	1	57	4	67	3	58	4	139
	Bond & Weld	2	9	1	9	3	9	9	9	1	9	0	10	2	9	3	9	0	10	0	10	
	All	100	1	47	6	99	1	83	2	58	5	53	5	86	2	60	5	67	4	58	5	
144	Plate	100	0	65	3	99	0	69	3	81	1	32	6	93	0	55	4	83	1	17	8	144
	Bond & Weld	0	10	18	8	4	9	0	10	7	9	3	9	4	9	7	9	8	9	8	9	
	All	100	1	83	2	103	0	69	4	88	2	35	7	97	1	62	4	91	1	25	8	
146	Plate	25	7	3	9	46	5	28	7	57	4	45	5	43	5	25	7	8	9	8	9	146
	Bond & Weld	27	7	19	8	43	5	38	6	16	8	8	9	29	7	22	7	8	9	42	5	
	All	52	5	22	8	89	2	66	4	73	3	53	5	72	3	47	6	16	9	50	6	
147	Plate	97	0	31	6	57	4	34	6	93	0	75	2	82	1	47	5	58	4	0	10	147
	Bond & Weld	10	9	37	6	59	4	72	2	15	8	25	7	28	7	45	5	50	5	58	4	
	All	107	0	68	4	116	0	106	0	108	0	100	1	110	0	92	1	108	0	58	5	
149	Plate	96	0	83	1	72	2	57	4	66	3	56	4	77	2	64	3	50	5	0	10	149
	Bond & Weld	9	9	13	8	9	9	0	10	7	9	24	7	8	9	12	8	25	7	25	7	
	All	105	0	96	1	81	2	57	5	73	3	80	3	85	2	76	3	75	3	25	8	
150	Plate	94	0	26	7	28	7	24	7	84	1	44	5	69	3	31	6	83	1	25	7	150
	Bond & Weld	4	9	22	7	76	2	52	4	15	8	6	9	32	6	26	7	42	5	33	6	
	All	98	1	48	6	104	0	76	3	99	1	50	6	101	0	57	5	125	0	58	5	

Determination of Rank - (All Failures)

Range Subdivisions	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101 & over	Range
Rank Number	10	9	8	7	6	5	4	3	2	1	0	Rank

Table 14 . - SUMMARY OF RATINGS AND WEIGHTED RANKS - As Rolled Plates.

Steel Number			139			144			146			147			149			150			Ranges of Ratings			
																					Best		Worst	
Basis of Rating	Weight Factor	Plate Size	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank	Rating	Rank
Steels Welded and Tested at All Temperatures -20°F to 70°F																								
Angle at Maximum Load	3	1/4"	59x	4	12	52	0	0	65	7	21	62	5	15	59x	4	12	57	3	9	65	7	52	0
Average angle for	3	1/2"	56x	2	6	60	4	12	68	8	24	64	6	18	63	6	18	62	5	15	68	8	56x	2
all specimens tested	3	3/4"	63x	6	18	54	1	3	64	6	18	60	4	12	59	4	12	58	3	9	64	6	54	1
	6	All	59.3x	4	24	55.3	2	12	65.7	7	42	62.0	5	30	60.3	4	24	59.0	4	24	65.7	7	55.3	2
Total Wtd. Rank	15				60			27			105			75			66			57				
Deviations Below 60°	3	1/4"	316x	6	18	832	1	3	28	9	27	50	9	27	284x	7	21	457	5	15	28	9	832	1
of individual angles	3	1/2"	700x	3	9	202	7	21	37	9	27	134	8	24	197	8	24	209	7	21	37	9	700x	3
at maximum load.	3	3/4"	129x	8	24	567	4	12	13	9	27	213	7	21	291	7	21	347	6	18	13	9	567	4
$= 100\Sigma(60° - A)/N$	6	All	380x	6	36	533	4	24	26	9	54	132	8	48	256	7	42	338	6	36	26	9	533	4
Total Wtd. Rank	15				87			60			135			120			108			90				
Plate Failures	2	1/4"	98	0	0	100	0	0	25	7	14	97	0	0	96x	0	0	94	0	0	25	7	100	0
Percent of specimens	2	1/2"	96	0	0	99	0	0	46	5	10	57	4	8	72	2	4	28	7	14	28	7	99	0
tested showing fail-	2	3/4"	57	4	8	81	1	2	57	4	8	93	0	0	66	3	6	84	1	2	57	4	93	0
ures in plate metal.	6	All	84	1	6	93	0	0	43	5	30	82	1	6	77	2	12	69	3	18	43	5	93	0
Total Wtd.Rank	12				14			2			62			14			22			34				
All Failures - Percent	1	1/4"	100	1	1	100	1	1	52	5	5	107	0	0	105x	0	0	98	1	1	52	5	107	0
of specimens tested	1	1/2"	99	1	1	103	0	0	89	2	2	116	0	0	81	2	2	104	0	0	81	2	116	0
showing failures in	1	3/4"	58	5	5	88	2	2	73	3	3	108	0	0	73	3	3	99	1	1	58	5	108	0
plate, bond, or weld	2	All	86	2	4	97	1	2	72	3	6	110	0	0	85	2	4	101	0	0	72	3	110	0
Total Wtd. Rank	5				11			5			16			0			9			2				
Maximum Load	1	1/4"	3860	2	2	5400	10	10	4210	4	4	4430	5	5	4620x	6	6	4550	5	5	5400	10	3860	2
Average for all	1	1/2"	6430	2	2	8120	8	8	7410	5	5	7790	6	6	7490	5	5	7950	7	7	8120	8	6430	2
specimens tested	1	3/4"	9880	5	5	10660	9	9	10690	9	9	11150	10	10	10420	8	8	9500	3	3	11150	10	9500	3
Total Wtd. Rank	3				9			27			18			21			19			15				
Total Weighted Rank	10	1/4"			33			14			71			47			39			30		71		14
for all rating	10	1/2"			18			41			68			56			53			57		68		18
factors combined.	10	3/4"			60			28			65			43			50			33		65		28
	20	All			70			38			132			84			82			78		132		38
Total -All Sizes	50				181			121			336			230			224			198		336		121
Relative Order No. (*)				(5)			(6)			(1)			(2)			(3)			(4)					
Steels Welded and Tested at 70°F (Room Temperature) only.																								
Angle at Maximum Load	3	1/4"	--	8*	24	61	5	15	65	7	21	60	4	12	60	4	12	60	4	12	65	7	60	4
	3	1/2"	70x	9	27	56	2	6	75	10	30	73	10	30	69	9	27	68	8	24	75	10	56	2
	3	3/4"	68	8	24	51	0	0	62	5	15	63	6	18	67	8	24	50	0	0	68	8	50	0
	6	All	69.0x	9	54	56.0	2	12	67.3	8	48	65.3	7	42	65.3	7	42	59.3	4	24	69.0x	9	56.0	2
Deviations Below 60°	3	1/4"	--	10*	30	25	9	27	0	10	30	50	9	27	150	8	24	175	8	24	0	10	175	8
	3	1/2"	0x	10	30	500	5	15	0	10	30	0	10	30	0	10	30	0	10	30	0	10	500	5
	3	3/4"	0	10	30	925	0	0	0	10	30	0	10	30	0	10	30	1000	0	0	0	10	1000	0
	6	All	0x	10	60	483	5	30	0	10	60	17	9	54	50	9	54	392	6	36	0	10	483	5
Plate Failures - %	12	All	67	3	36	83	1	12	8	9	108	58	4	48	50	5	60	83	1	12	8	9	83	1
All Failures	5	All	67	4	20	91	1	5	16	9	45	108	0	0	75	3	15	125	0	0	16	9	125	0
Maximum Load	1	1/4"	3755	1	1	5100	8	8	3968	2	2	4051	3	3	4745	6	6	4345	4	4	5100	8	3755	1
	1	1/2"	5810	0	0	7570	6	6	6962	4	4	7150	4	4	7062	4	4	7850	7	7	7850	7	5810	0
	1	3/4"	9450	3	3	10210	7	7	10300	7	7	10600	9	9	10100	6	6	8975	0	0	10600	9	8975	0
Total Weighted Rank Relative Order No. (*)	50	Total		(2)	339		(6)	143		(1)	430		(4)	307		(3)	334		(5)	173		430		143

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Table 15.- SUMMARY OF RATINGS AND WEIGHTED RANKS- Normalized Plates.

Steel Number			139			144			146			147			149			150			Ranges of Ratings			
Basis of Rating	Weight Factor	Plate Size	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Rating	Rank No.	Wtd. Rank	Best		Worst	
																					Rating	Rank	Rating	Rank
Steels Welded and Tested at All Temperatures -20°F to 70°F																								
Angle at Maximum Load	3	1/4"	66	7	21	61	5	15	66	7	21	64	6	18	58x	3	9	62	5	15	66	7	58x	3
Average angle for	3	1/2"	65x	7	21	66	7	21	68	8	24	68	8	24	64	6	18	64	6	18	68	8	64	6
all specimens tested	3	3/4"	63	6	18	61	5	15	64	6	18	62	5	15	60	4	12	62	5	15	64	6	60	4
	6	All	64.7x	6	36	62.7	5	30	66.0	7	42	64.7	6	36	60.7	4	24	62.7	5	30	66.0	7	60.7	4
Total Wtd. Rank	15				96			81			105			93			63			78				
Deviations Below 60°	3	1/4"	4	9	27	172	8	24	37	9	27	35	9	27	442x	5	15	209	7	21	4	9	442x	5
of individual angles	3	1/2"	257x	7	21	40	9	27	52	9	27	24	9	27	209	7	21	194	8	24	24	9	257	7
at maximum load	3	3/4"	158	8	24	110	8	24	17	9	27	70	9	27	193	8	24	110	8	24	17	9	193	8
$=100\Sigma(60°-A)/N$	6	All	135	8	48	107	8	48	35	9	54	43	9	54	268	7	42	171	8	48	35	9	268	7
Total Wtd. Rank	15				120			123			135			135			102			117				
Plate Failures	2	1/4"	46	5	10	65	3	6	3	9	18	31	6	12	83x	1	2	26	7	14	3	9	83x	1
Percent of specimens	2	1/2"	74	2	4	69	3	6	28	7	14	34	6	12	57	4	8	24	7	14	24	7	74	2
tested showing fail-	2	3/4"	53	4	8	32	6	12	45	5	10	75	2	4	56	4	8	44	5	10	32	6	75	2
ures in plate metal	6	All	57	4	24	55	4	24	25	7	42	47	5	30	64x	3	18	31	6	36	25	7	64	3
Total Wtd. Rank	12				46			48			84			58			36			74				
All Failures - Percent	1	1/4"	47	6	6	83	2	2	22	8	8	68	4	4	96x	1	1	48	6	6	28	8	96x	1
of specimens tested	1	1/2"	83	2	2	69	4	4	66	4	4	106	0	0	57	5	5	76	3	3	57	5	106	0
showing failures in	1	3/4"	53	5	5	35	7	7	53	5	5	100	1	1	80	3	3	50	6	6	35	7	100	1
plate, bond, or weld	2	All	60	5	10	62	4	8	47	6	12	92	1	2	76	3	6	57	5	10	47	6	92	1
Total Wtd. Rank	5				23			21			29			7			15			25				
Maximum Load	1	1/4"	3840	2	2	4670	6	6	3840	2	2	4070	3	3	4610x	6	6	3840	2	2	4670	6	3840	2
Average for all	1	1/2"	6430	2	2	7700	6	6	7250	5	5	7560	6	6	7260	5	5	7300	5	5	7700	6	6430	2
specimens tested	1	3/4"	9580	3	3	9230	2	2	10310	7	7	10680	9	9	10230	7	7	9170	1	1	10680	9	9170	1
Total Wtd. Rank	3				7			14			14			18			18			8				
Total Weighted Rank	10	1/4"			66			53			76			64			33			58		76		33
for all rating	10	1/2"			50			64			74			69			57			64		74		50
Factors combined	10	3/4"			58			60			67			56			54			56		67		54
	20	All			118			110			150			122			90			124		150		90
Total - All Sizes	50				292			287			367			311			234			302		367		234
Relative Order No. (*)				(4)			(5)			(1)			(2)			(6)			(3)					
Steels Welded and Tested at 70°F (Room Temperature) only.																								
Angle at Maximum Load	3	1/4"	65	7	21	72	10	30	61	5	15	62	5	15	68	8	24	69	9	27	72	10	61	5
	3	1/2"	68	8	24	68	8	24	67	8	24	69	9	27	69	9	27	68	8	24	69	9	67	8
	3	3/4"	66	7	21	64	6	18	66	7	21	63	6	18	66	7	21	66	7	21	66	7	63	6
	6	All	66.3	7	42	68.0	8	48	64.7	6	36	64.7	6	36	67.7	8	48	67.7	8	48	68.0	8	64.7	6
Deviations Below 60°	3	1/4"	0	10	30	0	10	30	500	5	15	200	8	24	0	10	30	0	10	30	0	10	500	5
	3	1/2"	0	10	30	0	10	30	0	10	30	0	10	30	0	10	30	0	10	30	0	10	0	10
	3	3/4"	0	10	30	25	9	27	0	10	30	0	10	30	0	10	30	0	10	30	0	10	25	9
	6	All	0	10	60	8	9	54	167	8	48	67	9	54	0	10	60	0	10	60	0	10	167	8
Plate Failures	12	All	58	4	48	17	8	96	8	9	108	0	10	120	0	10	120	25	7	84	0	10	58	4
All Failures	5	All	58	5	25	25	8	40	50	6	30	58	5	25	25	8	40	58	5	25	25	8	58	5
Maximum Load	1	1/4"	3687	1	1	4685	6	6	3603	0	0	3808	2	2	4360	4	4	3860	2	2	4685	6	3603	0
	1	1/2"	6162	1	1	7655	6	6	6825	3	3	7288	5	5	6750	3	3	7112	4	4	7655	6	6162	1
	1	3/4"	9088	1	1	8962	0	0	9738	4	4	10050	6	6	10050	6	6	8962	0	0	10050	6	8962	0
Total Weighted Rank	50	Total			334			409			364			392			443			385		443		334
Relative Order No. (*)				(6)			(2)			(5)			(3)			(1)			(4)					

Table 9. - ANGLES OF BEND AT MAXIMUM LOAD.

Plate Size		1/4"						1/2"						3/4"						All Sizes Combined				Size
Steel No. & Cond.	Test Temp °F	Weld Temperature, °F 70°	10°	0°	-10°	-20°	Rank	Weld Temperature, °F 70°	10°	0°	-10°	-20°	Rank	Weld Temperature, °F 70°	10°	0°	-10°	-20°	Rank	W & T at 70°F Ave.	Rank	W & T All Temp. Ave.	Rank	Steel No. & Cond.
139 AR	70	--	47x	56x	64x	59x	–	70x	56x	57x	59x	63x	9	68	66x	65x	64x	67x	8	69.0x	9			139 AR
	10	66		54		61		56		52		66		65		62		60						
	0	63		65		58		57		55		64		63		66		61						
	-10	65		61		57		43		50		51		66		52		66						
	-20	60		51		55		55		56		45		60		60		63						
	Ave.	All Temperatures				59x	4					56x	2					63x	6			59.3x	4	
139 N	70	65	67	66	65	67	7	68	71x	67x	70x	62x	8	66	66	64	62	65	7	66.3	7			139 N
	10	66		60		65		64		69		63		62		64		64						
	0	64		63		66		63		67		63		67		63		66						
	-10	66		65		66		67		52		70		67		56		54						
	-20	68		66		70		57		62		63		63		54		64						
	Ave.	All Temperatures				66	7					65x	7					63	6			64.7x	6	
144 AR	70	61	53	47	58	54	5	56	54	56	60	57	2	51	50	48	48	51	0	56.0	2			144 AR
	10	49		48		52		56		61		62		57		60		59						
	0	52		46		47		63		63		62		58		56		58						
	-10	53		52		55		61		59		63		55		57		56						
	-20	52		51		50		60		69		62		60		48		54						
	Ave.	All Temperatures				52	0					60	4					54	1			55.3	2	
144 N	70	72	66	66	65	63	10	68	60	66	67	64	8	64	58	58	60	64	6	68.0	8			144 N
	10	61		62		57		64		65		67		63		64		65						
	0	62		59		51		67		66		63		62		59		64						
	-10	61		59		53		67		64		70		56		58		60						
	-20	56		65		62		71		67		62		68		64		58						
	Ave.	All Temperatures				61	5					66	7					61	5			62.7	5	
146 AR	70	65	—	66	65	65	7	75	67	67	69	69	10	62	65	64	66	63	5	67.3	8			146 AR
	10	65		70		63		68		68		67		65		64		65						
	0	65		69		63		74		61		64		65		63		64						
	-10	64		59		63		73		69		65		66		68		63						
	-20	66		63		64		72		70		63		62		63		67						
	Ave.	All Temperatures				65	7					68	8					64	6			65.7	7	
146 N	70	61	67	65	66	66	5	67	69	68	69	68	8	66	65	65	63	64	7	64.7	6			146 N
	10	68		70		61		72		69		70		64		62		62x						
	0	67		68		65		70		70		67		64		66		66						
	-10	66		64		68		71		53		72		60		64		64						
	-20	69		66		72		61		67		70		59		64		68						
	Ave,	All Temperatures				66	7					68	8					64	6			66.0	7	
147 AR	70	60	63	61	60	64	4	73	56	58	62	59	10	63	59	62	62	61	6	65.3	7			147 AR
	10	64		60		60		68		65		65		59		64		62						
	0	62		61		61		69		67		69		65		63		63						
	-10	60		62		63		64		60		56		62		54		55						
	-20	61		64		64		69		65		57		62		54		49						
	Ave.	All Temperatures				62	5					64	6					60	4			62.0	5	
147 N	70	62	64	64	64	65	5	69	67	62	64	66	9	63	63	64	66	62	6	64.7	6			147 N
	10	63		58		63		69		72		68		59		65		66						
	0	68		64		62		69		65		70		61		59		62						
	-10	69		65		64		70		71		71		63		62		64						
	-20	64		65		66		56		75		67		57		66		58						
	Ave.	All Temperatures				64	6					68	8					62	5			64.7	6	
149 AR	70	60	75	58	57	58	4	69	62	64	63	62	9	67	66	60	65	65	8	65.3	7			149 AR
	10	60		60		48		66		57		58		62		62		54						
	0	--		60		59		66		66		70		58		62		51						
	-10	--		60		61		70		59		51		60		59		55						
	-20	--		56		58		71		56		61		52		56		55						
	Ave.	All Temperatures				59x	4					63	6					59	4			60.3	4	
149 N	70	68	63	65	61	64	8	69	65	63	63	63	9	66	66	60	61	64	7	67.7	8			149 N
	10	--		65		60		69		66		59		67		62		53						
	0	--		62		52		63		65		64		60		61		60						
	-10	--		52		60		68		64		56		59		58		52						
	-20	--		46		41		71		58		59		57		54		57						
	Ave.	All Temperatures				58x	3					64	6					60	4			60.7	4	
150 AR	70	60	55	50	54	60	4	68	59	63	56	53	8	50	64	66	66	63	0	59.3	4			150 AR
	10	59		40		67		67		70		69		61		55		62						
	0	54		66		62		61		68		62		61		54		61						
	-10	55		58		57		64		59		63		51		60		56						
	-20	53		57		56		57		59		60		49		54		58						
	Ave.	All Temperatures				57	3					62	5					58	3			59.0	4	
150 N	70	69	54	56	60	49	9	68	61	63	62	63	8	66	64	64	64	68	7	67.7	8			150 N
	10	70		72		69		66		72		48		67		62		61						
	0	68		67		59		71		72		64		62		61		59						
	-10	67		59		60		69		69		70		60		58		57						
	-20	60		55		62		62		66		42		56		62		64						
	Ave.	All Temperatures				62	5					64	6					62	5			62.7	5	

Determination of Rank

Range Subdivisions	Under 52.9	53-54.9	55-56.9	57-58.9	59-60.9	61-62.9	63-64.9	65-66.9	67-68.9	69-70.9	71- & over	Range Subdivisions
Rank Numbers	0	1	2	3	4	5	6	7	8	9	10	Rank Numbers

Table 11. PLATE FAILURES.

Steel No. & Cond.	Test Temp. °F	1/4" Weld Temp. °F 70	10	0	-10	-20	1/4" Failures Tot.	%	1/2" Weld Temp. °F 70	10	0	-10	-20	1/2" Failures Tot.	%	3/4" Weld Temp. °F 70	10	0	-10	-20	3/4" Failures Tot.	%	All Sizes Combined Weld Temp. °F 70	10	0	-10	-20	All Sizes Failures Tot.	%	Welded & Tested at 70°F	Steel No.
139 AR	70	4	4	4	2/2	4	18x	100	4	2	4	4	3	17	85	0	3	2	2	1	8	40	8					43x	74		139 AR
	10	3		4		4	11	92	4		4		4	12	100	2		4		1	7	58						30	83		
	0	4		4		4	12	100	4		4		4	12	100	1		2		2	5	42						29	81		
	-10	4		4		4	12	100	4		4		4	12	100	2		4		3	9	75						33	92		
	-20	4		4		4	12	100	4		4		4	12	100	3		4		3	10	83						34	94		
Total Failed		19	4	20	2	20	65		20	2	20	4	19	65		8	3	16	2	10	39		47	9	56	8	49	169		8	
Total Tested					x		66							68							68							202		12	
% Failed		95		100		100		98	100		100		95		96	40		80		50		57	78		93		82		84	67	
Rank								0							0							4							1	3	
139 N	70	3	0	0	1	1	5	25	4	2	3	1	1	11	55	0	0	1	0	3	4	20	7					20	33		139 N
	10	1		4		1	6	50	4		4		3	11	92	2		2		2	6	50						23	64		
	0	2		1		2	5	42	2		3		3	8	67	2		3		3	8	67						21	58		
	-10	1		3		2	6	50	3		4		2	9	75	2		4		4	10	83						25	69		
	-20	2		3		• 4	9	75	3		4		4	11	92	1		3		4	8	67						28	78		
Total Failed		9	0	11	1	10	31		16	2	18	1	13	50		7	0	13	0	16	36		32	2	42	2	39	117		7	
Total Tested							68							68							68							204		12	
% Failed		45		55		50		46	80		90		65		74	35		65		80		53	53		70		65		57	58	
Rank								5							2							4							4	4	
144 AR	70	4	4	4	4	4	20	100	4	4	3	4	4	19	95	2	4	4	3	4	17	85	10					56	93		144 AR
	10	4		4		4	12	100	4		4		4	12	100	2		3		3	8	67						32	89		
	0	4		4		4	12	100	4		4		4	12	100	4		2		4	10	83						34	94		
	-10	4		4		4	12	100	4		4		4	12	100	2		3		4	9	75						33	92		
	-20	4		4		4	12	100	4		4		4	12	100	3		4		4	11	92						35	97		
Total Failed		20	4	20	4	20	68		20	4	19	4	20	67		13	4	16	3	19	55		53	12	55	11	59	190		10	
Total Tested							68							68							68							204		12	
% Failed		100		100		100		100	100		95		100		99	65		80		95		81	88		92		98		93	83	
Rank								0							0							1							0	1	
144 N	70	0	3	4	3	4	14	70	0	4	4	3	3	14	70	2	0	2	0	0	4	20	2					32	53		144 N
	10	3		4		4	11	92	1		4		2	7	58	0		0		1	1	8						19	53		
	0	0		2		3	5	42	1		4		2	7	58	0		0		0	0	0						12	33		
	-10	4		2		4	10	83	1		4		4	9	75	3		4		1	8	67						27	75		
	-20	2		1		1	4	33	2		4		4	10	83	4		4		1	9	75						23	64		
Total Failed		9	3	13	3	16	44		5	4	20	3	15	47		9	0	10	0	3	22		23	7	43	6	34	113		2	
Total Tested							68							68							68							204		12	
% Failed		45		65		80		65	25		100		75		69	45		50		15		32	38		72		57		55	17	
Rank								3							3							6							4	8	
146 AR	70	1	-	4	0	0	5x	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1					5	9		146 AR
	10	0		2		0	2	17	2		2		1	5	42	2		4		0	6	50						13	36		
	0	0		1		1	2	17	2		4		2	8	67	4		4		4	12	100						22	61		
	-10	0		1		1	2	17	1		4		4	9	75	3		3		4	10	83						21	58		
	-20	1		2		2	5	42	3		2		4	9	75	3		4		4	11	92						25	69		
Total Failed		2	x	10	0	4	16		8	0	12	0	11	31		12	0	15	0	12	39		22	0	37	0	27	86		1	
Total Tested							64							68							68							200		12	
% Failed		10		50		20		25	40		60		55		46	60		75		60		57	37		62		45		43	8	
Rank								7							5							4							5	9	
146 N	70	0	0	0	0	0	0	0	1	0	0	0	0	1	5	0	0	0	0	0	0	0	1					1	2		146 N
	10	1		0		0	1	8	1		1		1	3	25	0		2		1/2	3x	30						7	19		
	0	0		0		0	0	0	0		1		0	1	8	0		4		3	7	58						8	22		
	-10	0		0		0	0	0	1		3		3	7	58	3		3		3	9	75						16	44		
	-20	1		0		0	1	8	2		3		2	7	58	3		4		4	11	92						19	53		
Total Failed		2	0	0	0	0	2		5	0	8	0	6	19		6	0	13	0	11	30		13	0	21	0	17	51		1	
Total Tested							68							68						x	66							202		12	
% Failed		10		0		0		3	25		40		30		28	30		65		61		45	22		35		29		25	8	
Rank								9							7							5							7	9	
147 AR	70	4	4	4	4	4	20	100	1	0	0	4	2	7	35	2	4	4	3	4	17	85	7					44	73		147 AR
	10	4		4		3	11	92	2		3		0	5	42	4		4		3	11	92						27	75		
	0	4		4		4	12	100	0		3		2	5	42	4		4		4	12	100						29	81		
	-10	4		4		4	12	100	4		3		4	11	92	3		4		4	11	92						34	94		
	-20	4		3		4	11	92	4		4		3	11	92	4		4		4	12	100						34	94		
Total Failed		20	4	19	4	19	66		11	0	13	4	11	39		17	4	20	3	19	63		48	8	52	11	49	168		7	
Total Tested							68							68							68							204		12	
% Failed		100		95		95		97	55		65		55		57	85		100		95		93	80		87		82		82	58	
Rank								0							4							0							1	4	
147 N	70	0	0	3	0	2	5	25	0	1	0	1	0	2	10	0	2	4	3	2	11	55	0					18	30		147 N
	10	1		4		1	6	50	1		0		1	2	17	2		4		2	8	67						16	44		
	0	0		1		0	1	8	2		1		1	4	33	3		4		3	10	83						15	42		
	-10	1		2		2	5	42	4		1		2	7	58	3		4		4	11	92						23	64		
	-20	0		3		1	4	33	4		3		1	8	67	4		4		3	11	92						23	64		
Total Failed		2	0	13	0	6	21		11	1	5	1	5	23		12	2	20	3	14	51		25	3	38	4	25	95		0	
Total Tested							68							68							68							204		12	
% Failed		10		65		30		31	55		25		25		34	60		100		70		75	42		63		42		47	0	
Rank								6							6							2							5	10	
149 AR	70	4	4	4	4	4	20	100	1	4	0	2	0	7	35	1	0	0	0	0	1	5	6					28	47		149 AR
	10	4		2		4	10	83	3		4		3	10	83	4		3		3	10	83						30	83		
	0	-		4		4	8x	100	2		4		3	9	75	4		4		4	12	100						29x	91		
	-10	-		4		4	8x	100	4		4		4	12	100	4		3		4	11	92						31x	97		
	-20	-		4		4	8x	100	3		4		4	11	92	4		3		4	11	92						30x	94		
Total Failed		8	4	18	4	20	54		13	4	16	2	14	49		17	0	13	0	15	45		38	8	47	6	49	148		6	
Total Tested		x					56							68							68		x					192		12	
% Failed		100		90		100		96x	65		80		70		72	85		65		75		66	79		78		82		77	50	
Rank								0							2							3							2	5	
149 N	70	0	4	4	4	4	16	80	0	0	0	0	0	0	0	0	0	0	0	1	1	5	0					17	28		149 N
	10	-		1		4	5x	63	0		3		3	6	50	1		3		4	8	67						19x	59		
	0	-		3		4	7x	87	3		4		4	11	92	3		3		2	8	67						26x	81		
	-10	-		4		3	7x	87	3		4		4	11	92	3		4		3	10	83						28x	88		
	-20	-		4		4	8x	100	3		4		4	11	92	3		4		4	11	92						30x	94		
Total Failed		0	4	16	4	19	43		9	0	15	0	15	39		10	0	14	0	14	38		19	4	45	4	48	120		0	
Total Tested		x					52							68							68		x					188		12	
% Failed		0		80		95		83x	45		75		75		57	50		70		70		56	43		75		80		64	0	
Rank								1							4							4							3	10	
150 AR	70	4	3	4	4	3	18	90	4	0	0	0	0	4	20	2	4	4	4	3	17	85	10					39	65		150 AR
	10	4		4		2	10	83	0		0		0	0	0	2		2		4	8	67						18	50		
	0	4		4		4	12	100	0		0		3	3	25	1		4		4	9	75						24	67		
	-10	4		4		4	12	100	0		3		2	5	42	3		4		4	11	92						28	78		
	-20	4		4		4	12	100	1		2		4	7	58	4		4		4	12	100						31	86		
Total Failed		20	3	20	4	17	64		5	0	5	0	9	19		12	4	18	4	19	57		37	7	43	8	45	140		10	
Total Tested							68							68							68							204		12	
% Failed		100		100		85		94	25		25		45		28	60		90		95		84	62		72		75		69	83	
Rank								0							7							1							3	1	
150 N	70	0	4	0	2	4	10	50	3	0	0	0	0	3	15	0	0	1	0	0	1	5	3					14	23		150 N
	10	0		0		1	1	8	0		0		1	1	8	0		2		1	3	25						5	14		
	0	1		1		1	3	25	0		0		1	1	8	2		4		0	6	50						10	28		
	-10	1		0		1	2	17	0		2		2	4	33	3		3		3	9	75						15	42		
	-20	1		0		1	2	17	3		1		3	7	58	3		4		4	11	92						20	56		
Total Failed		3	4	1	2	8	18		6	0	3	0	7	16		8	0	14	0	8	30		17	4	18	2	23	64		3	
Total Tested							68							68							68							204		12	
% Failed		15		5		40		26	30		15		35		24	40		70		40		44	28		30		38		31	25	
Rank								7							7							5							6	7	

Determination of Rank

Range Subdivisions	0	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	Range Subdivisions
Rank Numbers	10	9	8	7	6	5	4	3	2	1	0	Rank Numbers

Table 12. - BOND AND WELD FAILURES.

Steel No. & Cond.	Test Temp. °F	1/4" Weld Temp. °F 70	10	0	-10	-20	1/4" Failures Tot.	%	1/2" Weld Temp. °F 70	10	0	-10	-20	1/2" Failures Tot.	%	3/4" Weld Temp. °F 70	10	0	-10	-20	3/4" Failures Tot.	%	All Sizes Combined Weld Temp. °F 70	10	0	-10	-20	All Sizes Failures Tot.	%	Welded & Tested at 70°F	Steel No. & Cond.
139 AR	70	0	0	0	0/2	0	0x	0	0	2	0	0	0	2	10	0	0	0	0	0	0	0	0					2	3		139 AR
	10	0		0		0	0	0	0		0		0	0	0	0		0		0	0	0						0	0		
	0	0		1		0	1	8	0		0		0	0	0	0		0		0	0	0						1	3		
	-10	0		0		0	0	0	0		0		0	0	0	0		0		0	0	0						0	0		
	-20	0		0		0	0	0	0		0		0	0	0	0		1		0	1	8						1	3		
	Total Failed	0	0	1	0	0	1		0	2	0	0	0	2		0	0	1	0	0	1		0	2	2	0	0	4		0	
	Total Tested				x		66							68							68							202		12	
	% Failed	0		5		0		2	0		0		0		3	0		5		0		1	0		3		0		2	0	
	Rank							9							9							9							9	10	
139 N	70	0	0	0	0	0	0	0	0	0	1	3	0	4	20	0	0	0	0	0	0	0	0					4	7		139 N
	10	0		1		0	1	8	0		0		1	1	8	0		0		0	0	0						2	6		
	0	0		0		0	0	0	0		0		0	0	0	0		0		0	0	0						0	0		
	-10	0		0		0	0	0	0		0		1	1	8	0		0		0	0	0						1	3		
	-20	0		0		0	0	0	0		0		0	0	0	0		0		0	0	0						0	0		
	Total Failed	0	0	1	0	0	1		0	0	1	3	2	6		0	0	0	0	0	0		0	0	2	3	2	7		0	
	Total Tested						68							68							68							204		12	
	% Failed	0		5		0		1	0		5		10		9	0		0		0		0	0		3		3		3	0	
	Rank							9							9							10							9	10	
144 AR	70	0	0	0	0	0	0	0	0	0	0	1	0	1	5	1	0	0	0	1	2	10	1					3	5		144 AR
	10	0		0		0	0	0	0		1		1	2	17	0		0		0	0	0						2	6		
	0	0		0		0	0	0	0		0		0	0	0	0		0		0	0	0						0	0		
	-10	0		0		0	0	0	0		0		0	0	0	0		00		0	0	0						0	0		
	-20	0		0		0	0	0	0		0		0	0	0	3		0		0	3	25						3	8		
	Total Failed	0	0	0	0	0	0		0	0	1	1	1	3		4	0	0	0	1	5		4	0	1	1	2	8		1	
	Total Tested						68							68							68							204		12	
	% Failed	0		0		0		0	0		5		5		4	20		0		5		7	7		2		3		4	8	
	Rank							10							9							9							9	9	
144 N	70	0	1	0	0	0	1	5	0	0	0	0	0	0	0	1	0	0	0	0	1	5	1					2	3		144 N
	10	0		0		2	2	17	0		0		0	0	0	0		0		0	0	0						2	6		
	0	0		0		3	3	25	0		0		0	0	0	0		0		0	0	0						3	8		
	-10	0		3		0	3	25	0		0		0	0	0	1		0		0	1	8						4	11		
	-20	2		1		0	3	25	0		0		0	0	0	0		0		0	0	0						3	8		
	Total Failed	2	1	4	0	5	12		0	0	0	0	0	0		2	0	0	0	0	2		4	1	4	0	5	14		1	
	Total Tested						68							68							68							204		12	
	% Failed	10		20		25		18	0		0		0		0	10		0		0		3	7		7		8		7	8	
	Rank							8							10							9							9	9	
146 AR	70	1	-	0	0	1	2x	13	0	2	3	1	4	10	50	0	2	0	0	3	5	25	1					17x	30		146 AR
	10	0		2		1	3	25	1		2		4	7	58	2		0		1	3	25						13	36		
	0	0		1		1	2	17	3		3		3	9	75	0		0		0	0	0						11	31		
	-10	0		1		3	4	33	1		0		1	2	17	1		1		0	2	17						8	22		
	-20	2		2		2	6	50	0		0		1	1	8	1		0		0	1	8						8	22		
	Total Failed	3	x	6	0	8	17		5	2	8	1	13	29		4	2	1	0	4	11		12	4	15	1	- 25	57		1	
	Total Tested						64							68							68			x				200		12	
	% Failed	15		30		40		27	25		40		65		43	20		5		20		16	20		25		42		29	8	
	Rank							7							5							8							7	9	
146 N	70	1	0	2	0	3	6	30	0	2	3	0	3	8	40	4	0	0	1	0	5	25	5					19	32		146 N
	10	0		0		1	1	8	1		4		2	7	58	0		0		0/2	0x	0						8x	24		
	0	2		0		0	2	17	2		2		2	6	50	0		0		0	0	0						8	22		
	-10	1		0		0	1	8	0		2		1	3	25	0		0		0	0	0						4	11		
	-20	2		1		0	3	25	0		0		2	2	17	0		0		0	0	0						5	14		
	Total Failed	6	0	3	0	4	13		3	2	11	0	10	26		4	0	0	1	0	5		13	2	14	1	14	44		5	
	TOtal Tested						68							68						x	66						x	202		12	
	% Failed	30		15		20		19	15		55		50		38	20		0		0		8	22		23		24		22	42	
	Rank							8							6							9							7	5	
147 AR	70	0	0	0	2	0	2	10	4	4	4	3	4	19	95	2	0	0	0	1	3	15	6					24	40		147 AR
	10	1		0		0	1	8	2		2		4	8	67	1		0		0	1	8						10	28		
	0	0		0		0	0	0	3		2		4	9	75	0		0		1	1	8						10	28		
	-10	0		0		0	0	0	0		1		2	3	25	2		0		0	2	17						5	14		
	-20	0		2		2	4	33	0		0		1	1	8	3		0		0	3	25						8	22		
	Total Failed	1	0	2	2	2	7		9	4	9	3	15	40		8	0	0	0	2	10		18	4	11	5	19	57		6	
	TOtal Tested						68							68							68							204		12	
	% Failed	5		10		10		10	45		45		75		59	40		0		10		15	30		18		32		28	50	
	Rank							9							4							8							7	5	
147 N	70	3	0	1	1	0	5	25	2	3	4	4	4	17	85	2	2	0	2	1	7	35	7					29	48		147 N
	10	3		1		1	5	42	4		4		3	11	92	2		0		2	4	33						20	56		
	0	0		4		1	5	42	3		4		2	9	75	1		1		3	5	42						19	53		
	-10	1		1		1	3	25	2		4		3	9	75	0		0		0	0	0						12	33		
	-20	1		4		2	7	58	0		1		2	3	25	1		0		0	1	8						11	31		
	Total Failed	8	0	11	1	5	25		11	3	17	4	14	49		6	2	1	2	6	17		25	5	29	7	25	91		7	
	Total Tested						68							68							68							204		12	
	% Failed	40		55		25		37	55		85		70		72	30		5		30		25	42		48		42		45	58	
	Rank							6							2							7							5	4	
149 AR	70	0	3	0	0	0	3	15	2	0	0	0	4	6	30	1	0	0	0	0	1	5	3					10	17		149 AR
	10	0		2		0	2	17	0		0		0	0	0	0		1		0	1	8						3	8		
	0	-		0		0	0x	0	0		0		0	0	0	0		1		0	1	8						1x	3		
	-10	-		0		0	0x	0	0		0		0	0	0	0		1		0	1	8						1x	3		
	-20	-		0		0	0x	0	0		0		0	0	0	0		1		0	1	8						1x	3		
	Total Failed	0	3	2	0	0	5		2	0	0	0	4	6		1	0	4	0	0	5		3	3	6	0	4	16		3	
	Total Tested	x					56							68							68		x					192		12	
	% Failed	0		10		0		9x	10		0		20		9	5		20		0		7	6		10		7		8	25	
	Rank							9							9							9							9	7	
149 N	70	0	3	0	0	0	3	15	0	0	0	0	0	0	0	3	0	0	0	1	4	20	3					7	12		149 N
	10	-		3		0	3x	38	0		0		0	0	0	0		1		1	2	17						5x	16		
	0	-		1		0	1x	13	0		0		0	0	0	1		0		1	2	17						3x	9		
	-10	-		0		0	0x	0	0		0		0	0	0	2		0		0	2	17						2x	6		
	-20	-		0		0	0x	0	0		0		0	0	0	2		3		1	6	50						6x	19		
	Total Failed	0	3	4	0	0	7		0	0	0	0	0	0		8	0	4	0	4	16		8	3	8	0	4	23		3	
	Total Tested	x					52							68							68		x					188		12	
	% Failed	0		20		0		13x	0		0		0		0	40		20		20		24	18		13		7		12	25	
	Rank							8							10							7							8	7	
150 AR	70	0	1	0	0	0	1	5	2	4	4	4	4	18	90	3	0	1	0	0	4	20	5					23	38		150 AR
	10	0		0		2	2	17	4		4		4	12	100	1		0		0	1	8						15	42		
	0	0		0		0	0	0	4		4		1	9	75	4		0		0	4	33						13	36		
	-10	0		0		0	0	0	4		2		2	8	67	1		0		0	1	8						9	25		
	-20	0		0		0	0	0	3		2		0	5	42	0		0		0	0	0						5	14		
	Total Failed	0	1	0	0	2	3		17	[illegible]	16	4	11	52		9	0	1	0	0	10		26	5	17	4	13	65		5	
	Total Tested						68							68							68							204		12	
	% Failed	0		0		10		4	85		80		55		76	45		5		0		15	43		28		22		32	42	
	Rank							9							2							8							6	5	
150 N	70	0	0	0	0	0	0	0	2	4	3	4	3	16	80	2	0	0	0	0	2	10	4					18	30		150 N
	10	2		0		3	5	42	1		2		3	6	50	0		0		0	0	0						11	31		
	0	1		0		1	2	17	1		2		2	5	42	0		0		2	2	17						9	25		
	-10	0		2		3	5	42	3		1		2	6	50	0		0		0	0	0						11	31		
	-20	1		1		1	3	25	0		1		1	2	17	0		0		0	0	0						5	14		
	Total Failed	4	0	3	0	8	15		7	4	9	4	11	35		2	0	0	0	2	4		13	4	12	4	21	54		4	
	Total Tested						68							68							68							204		12	
	% Failed	20		15		40		22	35		45		55		52	10		0		10		6	22		20		35		26	33	
	Rank							7							4							9							7	6	

Determination of Rank

Range Subdivisions	0	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	Range Subdivisions
Rank Numbers	10	9	8	7	6	5	4	3	2	1	0	Rank Numbers

on the range of values found for each size, afford an approximate basis for comparison.

To determine the rank numbers, the total range of the property under consideration was divided into 11 subdivisions, which were given consecutive rank numbers from 0 to 10. A rank of 0 was assigned to the subdivision at the least desirable end of the range and a rank of 10 to that in the most desirable end of the range of values. High rank numbers then indicate the best steels, as judged on the basis of this particular property. The rank numbers also afford a means for comparing the effect of testing conditions, such as temperature of welding and testing, plate thickness, and heat treatment, since all of the rank numbers for any property were based on the same table of range subdivisions, except in the case of maximum load (table 8), in which different ranges were used for the different plate thicknesses.

These rank numbers for a particular property are used to indicate, by small numbers, which are easily compared, the relative merit of the steels under different conditions. These rank numbers are used also in the determination of the weighted rank (tables 14, 15, and 16), in which several rating factors are considered.

The maximum load usually increased with increase in thickness of the plate. The maximum loads for the normalized steels were generally lower than for the specimens of corresponding steels in the as-rolled condition.

The data of table 8 are shown graphically in figure 9, in which the average loads of each of the three thicknesses of plates are shown by means of the lengths of their respective bars.

Figures 10 and 11 show, respectively, the variation of maximum load with testing temperature and with the temperature at which the specimens were welded. The three groups of curves in each column represent the three plate sizes, ¾, ½, and ¼ in., reading from top to bottom. The data given in figure 9 are also shown in these figures by the double circles in the left of each column. The small "x" indicates that the data are incomplete for these points.

These two figures indicate that the maximum load increased as the temperature of testing was reduced from room temperature to −20° F, but that the relation between maximum load and the temperatures at which the specimens were welded was entirely random and independent of the testing temperature.

2. ANGLE AT MAXIMUM LOAD

The angles at maximum loads for each of the six steels under different conditions of welding and testing are given in table 9. The values are the average angles for four duplicate specimens tested under the same conditions. In each of the large boxes under the respective plate-size headings, the average angles for the respective welding temperatures indicated in the top box are read horizontally, and the variation with testing temperature, given in the second column of the table, is read vertically. The value in the upper left-hand corner of each box represents the average angle for the four specimens welded and tested at room temperature. The average angle for all specimens of one size and condition (normally 68) in the 17 combinations of welding and testing temperatures is given in the lower right-hand corner of each box. The relative rank of the steels is indicated in the columns headed "rank"; the rank for the room-temperature tests is found at the top of each small box, and that for

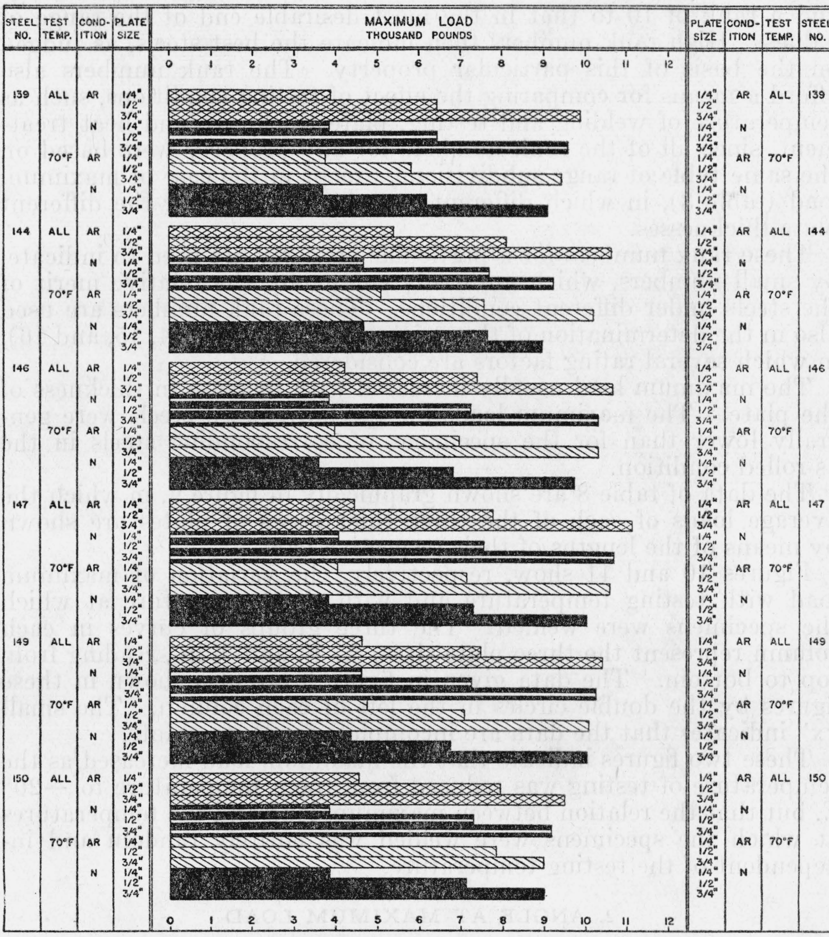

FIGURE 9.—*Maximum loads.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plates, welded and tested at 70° F.

the average of all combinations of welding and testing temperatures, at the bottom of the box.

The average angle and the rank for the three plate sizes combined are given in two columns at the right of the table, for the specimens welded and tested at room temperature (70° F) and for the average of all temperature combinations.

The principal data of table 9 are shown graphically in figure 12.

For specimens welded and tested at 70° F, the bending angles for all thicknesses were approximately the same for the as-rolled and normalized conditions. One outstanding exception was steel 144, in which the angles were considerably greater for the normalized condition than for the as-rolled condition. From tensile and microscopic studies it was believed that when rolled this steel had been finished

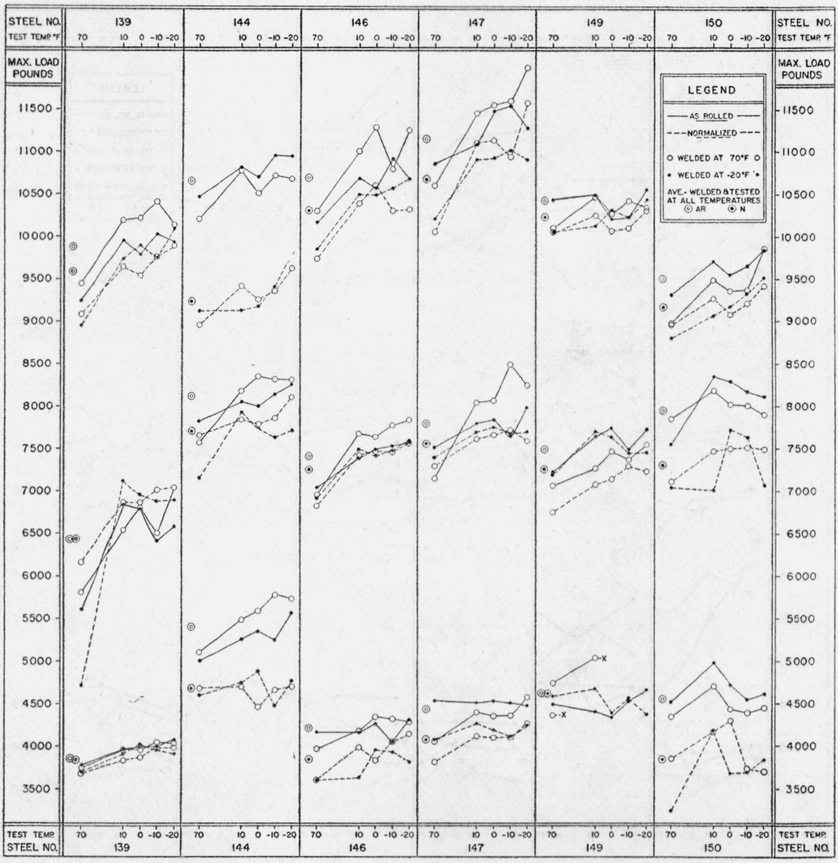

FIGURE 10.—*Relation of maximum loads to testing temperatures.*

"cold." This apparently contributed to the great differences in bending angles in the two conditions. The different sizes of plates were rolled from different heats of steel.

The ¼-in. plates of steel 149 and the ¼- and ¾-in. plates of steel 150 likewise bent to greater angles in the normalized condition than in the as-rolled. The plates were rolled from different heats.

Steels 139, 146, and 147 had uniform bending angles in the as-rolled and normalized conditions.

The variation in angle at maximum load with testing temperature is shown in figure 13, in which are plotted results of tests of specimens welded at 70° F and at −20° F in both the as-rolled and the normalized conditions and tested at different temperatures. These results show that the trend is toward lower angles at lower testing temperatures. This tendency is less marked in steels 139, 146, and 147 than in the others, indicating that testing temperatures have less influence on the angles at maximum load in these steels than on the other three.

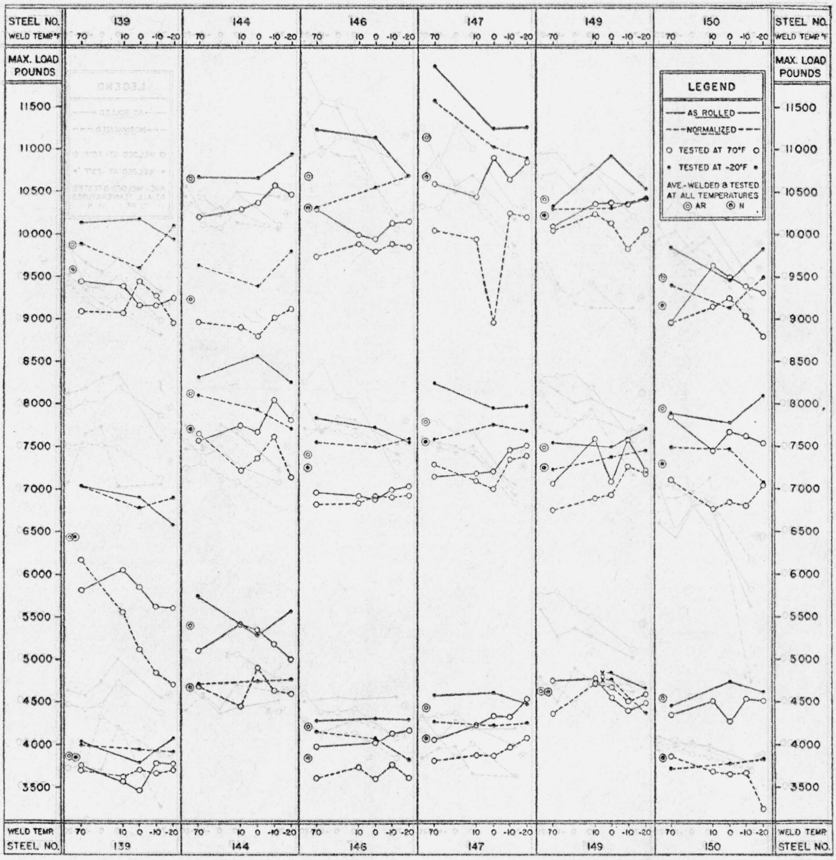

FIGURE 11.—*Relation of maximum loads to welding temperatures.*

The variation in angle at maximum load with welding temperatures is shown in figure 14, in which are plotted results of tests of steels welded at various temperatures and tested at 70° and −20° F in both the as-rolled and the normalized conditions. These results show that there is a slight tendency toward lower bending angles at lower welding temperatures, although the trend is not well marked. In general, low testing temperatures appeared to have more effect on bending angles at maximum load than the temperature of the plates before welding.

In the use of any statistical method of analysis for interpretation of data, some precaution must be taken to insure credit being given to the material which is uniform in properties as compared with one which

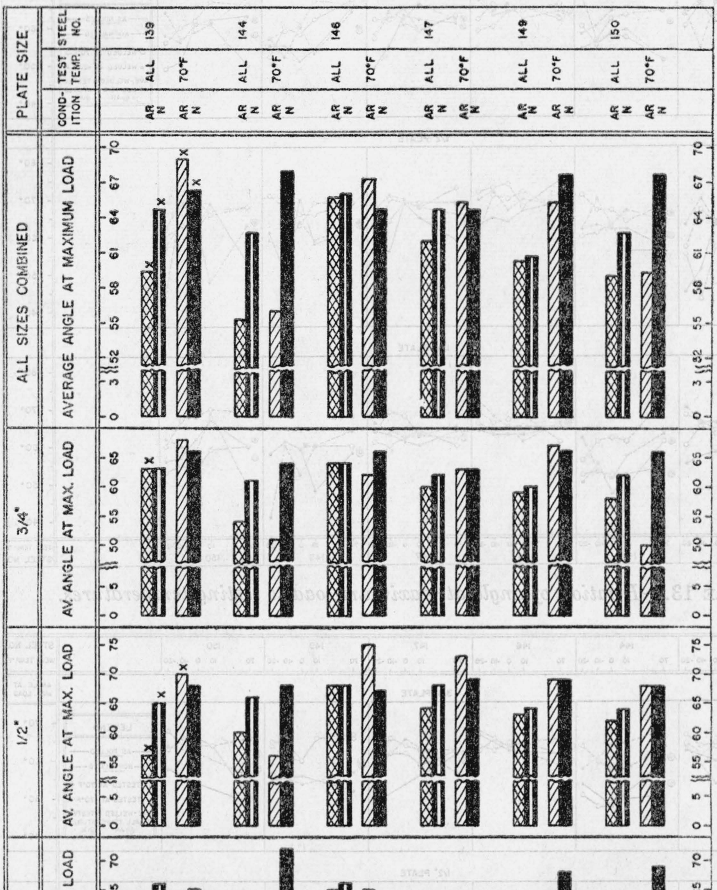

FIGURE 12.—*Angle of bend at maximum load.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plates, welded and tested at 70° F.

may have a high average for properties, but scatter considerably between the extremes. For this reason, a system was devised which would penalize in a final rating any lack of uniformity in angles at

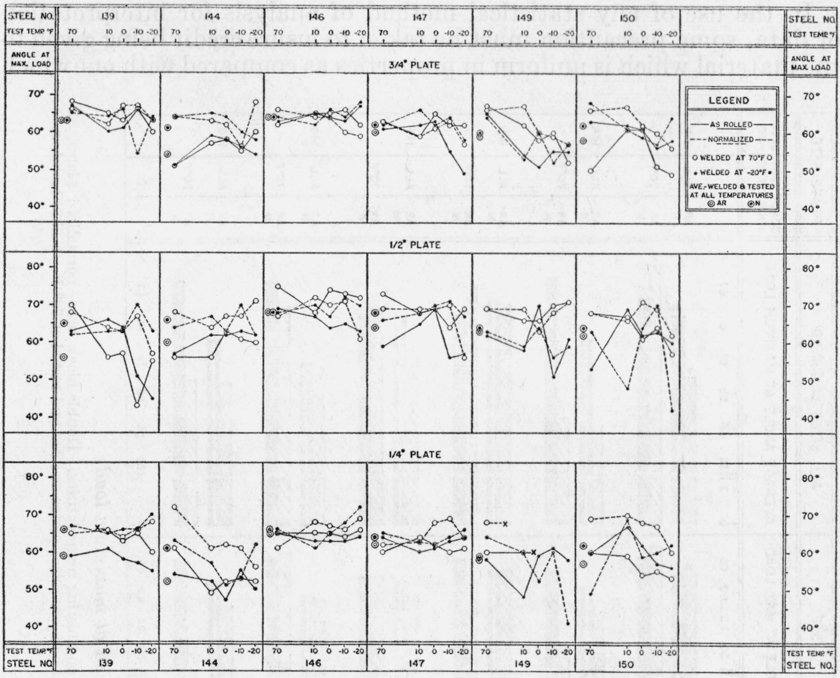

Figure 13.—*Relation of angle at maximum load to testing temperatures.*

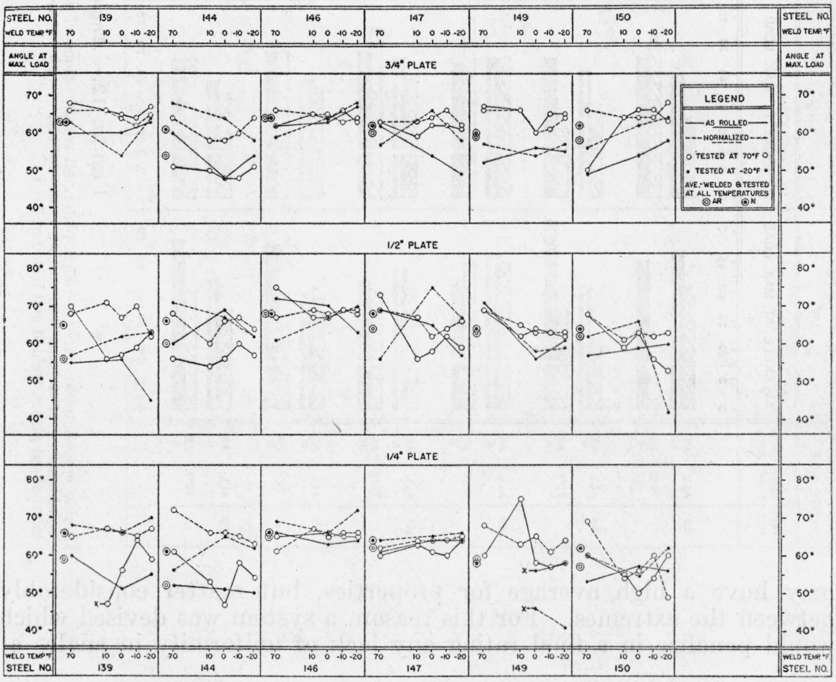

Figure 14.—*Relation of angle at maximum load to welding temperatures.*

maximum load for duplicate specimens in each group, although the average angle of a group might have been high. The deviations in angles are given in table 10. The values in the large boxes are the sums of the deviations below 60° of the angles for the individual specimens, tested at the combinations of welding and testing temperatures indicated respectively in the heading and the second column of the table. That is, if, for an individual specimen, the angle at maximum load is less than 60°, the difference, or 60° minus the angle, is taken as the deviation; if the angle is 60° or more, it is disregarded, since the interest is only in those specimens which show a low angle. The angle 60° was chosen arbitrarily as a value high enough to include any significantly low measurements of the angle, but not so high as to include average or above-average values, since if all of the angles showed a negative deviation from the reference angle, the average of these deviations would merely be another way of stating the average angle.

The figures in the large boxes of the table then represent the sum of these negative deviations for the four specimens tested at each temperature combination; if less than four specimens were tested, the figure appears as a fraction, the denominator representing the number of specimens. In the lower right-hand corner of each box the total deviation for all specimens is shown as the numerator of a fraction, the denominator representing the total number of specimens.

The rating is this fraction multiplied by 100—expressed mathematically, the rating is $100\Sigma(60°-A)/N$, where A is the angle at maximum load for each individual specimen in which this angle is less than 60° and N is the total number of specimens. The rating and the rank for the specimens welded and tested at room temperature are shown in the top part of the smaller boxes; and for the average of all temperature combinations in the lower part of these boxes. The rank is determined from the range of ratings by reference to the tabulation at the bottom of the table, as outlined in the discussion of table 8. It should be noted in this case that a high rating of deviations is undesirable; hence the rank numbers are assigned in reverse order, so that steels with low deviations have high rank numbers. The data of this table are shown graphically in figure 15, in which the length of the bars is proportional to the average deviation below 60° of the individual maximum load angles for the test groups indicated in the columns at the left. A long bar, indicating a large average deviation below 60°, may mean that the average angle is low; but if the average angle, as shown in figure 12, is above 60°, the deviations or scatter of the individual measurements are large. Either of these conditions is undesirable from the viewpoint of reliability of the weld as indicated by the angle at maximum load, so that in this figure a *short* bar indicates a steel with reasonably consistent bending angles and with an average angle above 60°.

3. FAILURES

Failures in the bend test occurred in three locations: (1) in the plate metal; (2) in the bond zone; and (3) in the weld metal. Failures in the plate metal were considered the least desirable. Table 11 lists the number of failures in the plate metal and table 12 in the bond zone and weld metal.

If both a plate failure and a bond or weld failure were observed in the same specimen, both failures were recorded in the respective tables.

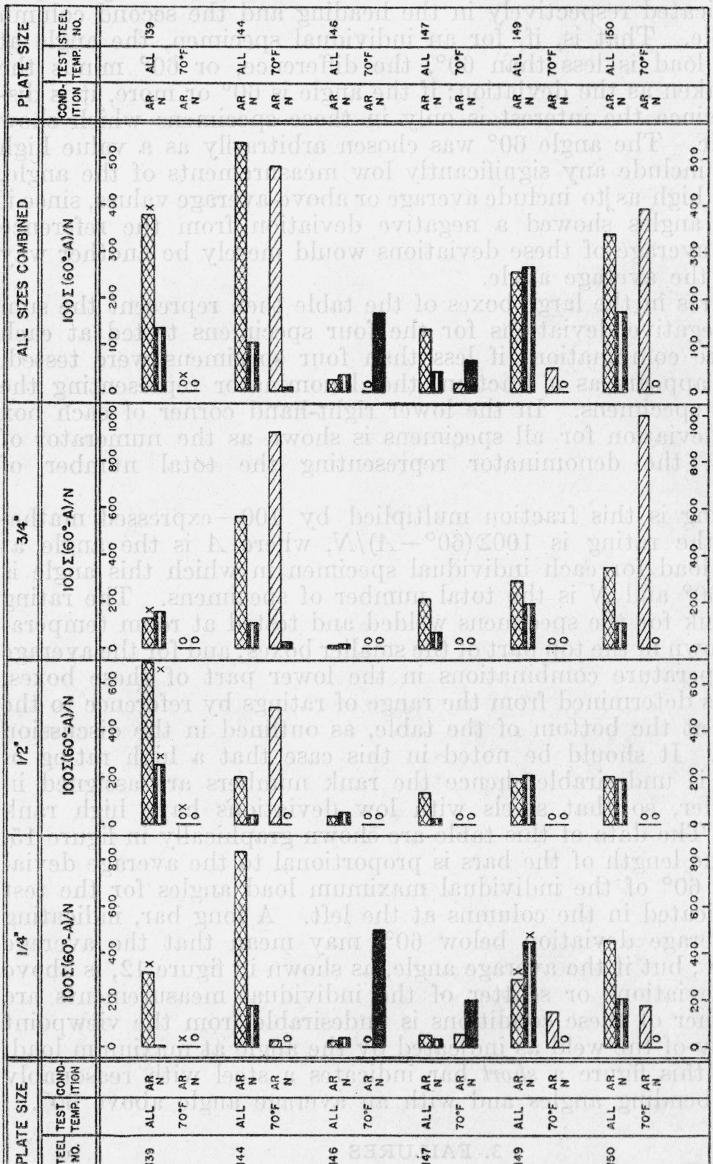

FIGURE 15.—*Deviations below 60° of individual angles at maximum load.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plate, welded and tested at 70° F.

The figures in the upper part of the large boxes represent the number of specimens which failed under the test conditions indicated in the column heads and the columns at the left. Four specimens were tested for each set of conditions, unless otherwise indicated by a fraction, in which the numerator represents the number of specimens which failed, and the denominator the number tested. The figures at the bottom of each box represent the percentage of failures for the entire groups of specimens welded at a given temperature and tested at all temperatures. The percentage values in the columns to the right of the boxes indicate the percentage of failures in the group of specimens tested at the given temperature but welded at different temperatures. At the bottom of these columns is the percentage of failures in the entire group, welded and tested at all temperature combinations, followed by the rank determined from the tabulation at the bottom of the sheet. The data for "all sizes combined" are obtained by cross-addition of the corresponding totals for each of the three sizes. The last column gives, for the specimens welded and tested at room temperature, the data indicated by the subheads in the first column, for all sizes combined.

Table 13 summarizes the results given in tables 11 and 12. The total is greater than 100 percent in several instances, because several of the specimens showed both types of failure, which were tabulated separately in tables 11 and 12. The data in table 13 are shown graphically in figure 16, and the variations in percentage of failures with testing and welding temperatures are shown in figures 17 and 18.

The percentage of plate failures is highest in the ¼-in. thicknesses and lowest in the ½-in. thicknesses in the as-rolled condition. In normalized plates, the percentage of plate failures increases as the plate thickness increases, being lowest in the ¼-in. plates and highest in the ¾-in. plates. There were fewer plate failures in the normalized condition than in the as-rolled condition.

Usually bond or weld failures did not occur when there was an early plate failure; therefore if there were many plate failures, there were few bond or weld failures. Probably for this reason the average percentage of bond and weld failures in ¼- and ¾-in. thicknesses was higher in the normalized than in the as-rolled condition.

In the as-rolled plates, the percentage of bond and weld failures was low in the ¼- and ¾-in. thicknesses and relatively high in the ½-in. thicknesses. In the normalized condition there were fewer bond and weld failures in the ¾-in. than in the ½-in. thicknesses.

All failures, including both plate and bond or weld failures were highest in the ½-in. thicknesses both as-rolled and normalized. Normalized plates, in general, had fewer failures of all types than as-rolled plates, in all thicknesses.

The number of plate failures increased, in almost every case, as the testing temperature was decreased. This increase was slightly more pronounced in the normalized than in the as-rolled condition.

The relation between plate failures and temperatures at which the plates were welded is not so pronounced as the relation to testing temperatures, but there was a slight increase in number of plate failures for specimens welded at lower temperatures.

The relationship of bond and weld failures to the welding and testing temperatures is overshadowed by the increase in plate failures at the lower temperatures. This has a decided effect on the number of bond or weld failures.

There is no indication, from these results, of any critical region of either welding or testing temperature, in the range 70° to −20° F., at which there was a sudden increase in the number of failures.

Considering all sizes combined and the averages of all combinations of welding and testing temperatures, steel 146 had the smallest number of plate failures and of all failures combined, in both the as-rolled and the normalized conditions. Plate failures were greatest in steel 144 in the as-rolled condition and in steel 149 in the normalized condition. Total failures were highest in steel 147 in both the as-rolled and normalized conditions, although most of these failures were in the bonds or welds.

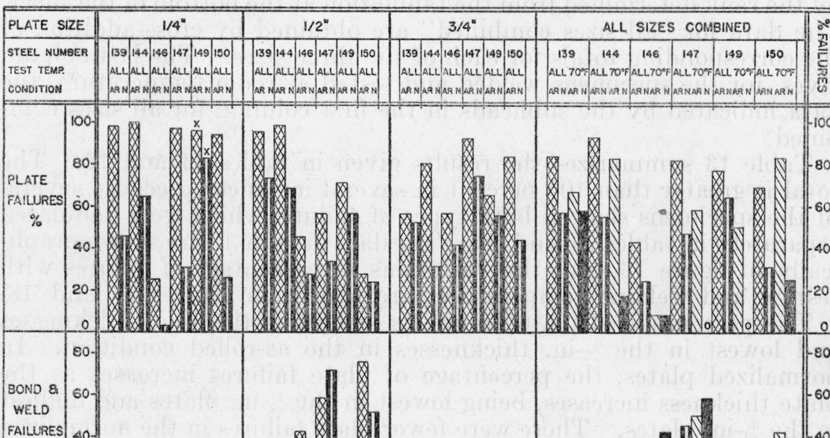

FIGURE 16.—*Failures of specimens.*

Double cross-hatched bars—as-rolled plates, all combinations of welding and testing temperatures. Double black bars—normalized plates, all combinations of welding and testing temperatures. Single cross-hatched bars—as-rolled plates, welded and tested at 70° F. Solid black bars—normalized plates, welded and tested at 70° F.

The relative merit of each steel as determined by the percentage of plate failures and the relation of plate failures to chemical, hardness, and tensile properties for each size separately will be considered in a later section.

Fractures in the T-bend specimens were classified as follows:

Type I. A crack which started in the bond zone at the toe of the fillet and followed the fusion zone under the weld, but did not turn into the plate metal.

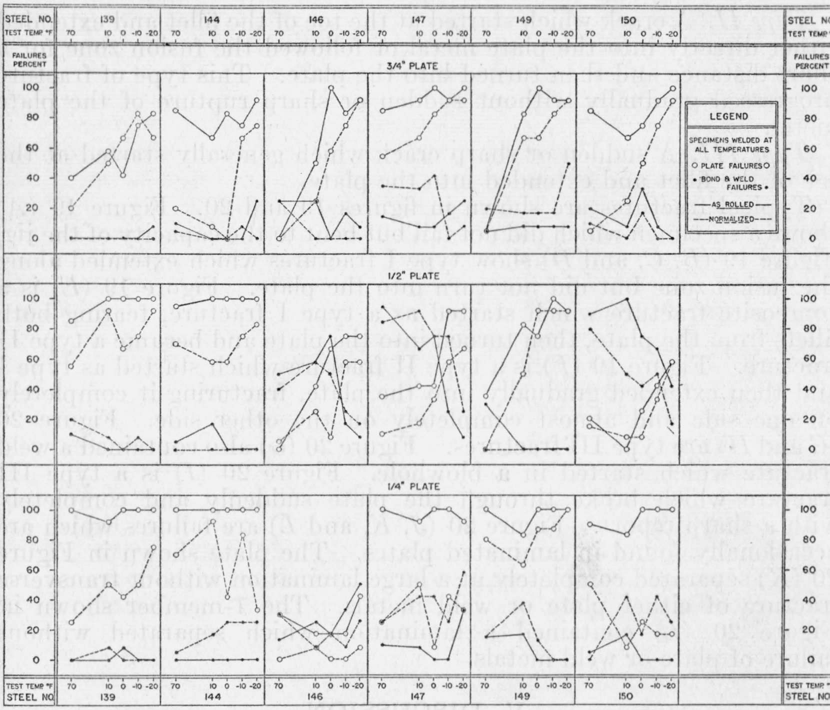

FIGURE 17.—*Relation of percentage of failures to testing temperatures.*

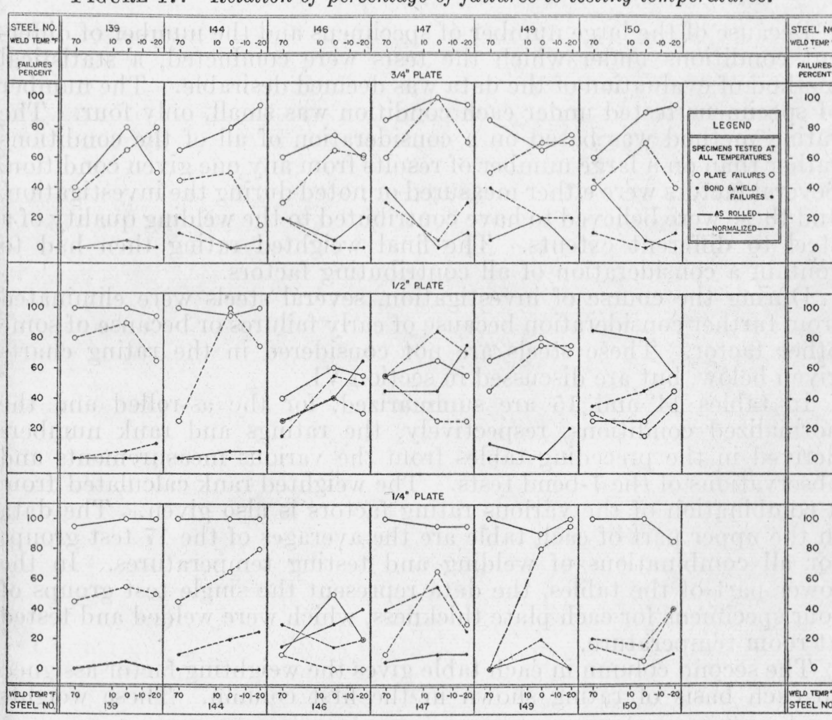

FIGURE 18.—*Relation of percentage of failures to welding temperatures.*

Type II. A crack which started at the toe of the fillet and extended either directly into the plate metal or followed the fusion zone for a short distance and then turned into the plate. This type of fracture progressed gradually without sudden or sharp rupture of the plate metal.

Type III. A sudden or sharp crack which generally started at the toe of the fillet and extended into the plate.

Typical fractures are shown in figures 19 and 20. Figure 19 (*A*) shows a specimen which did not fail but bent to the capacity of the jig. Figure 19 (*B*, *C*, and *D*) show type I fractures which extended along the fusion zone but did not turn into the plate. Figure 19 (*E*) is a composite fracture which started as a type I fracture, tearing both fillets from the plate, then turned into the plate and became a type II fracture. Figure 19 (*F*) is a type II fracture which started as type I and then extended gradually into the plate, fracturing it completely on one side and almost completely on the other side. Figure 20 (*G* and *H*) are type III fractures. Figure 20 (*G*) also contained a weld fracture which started in a blowhole. Figure 20 (*I*) is a type III fracture which broke through the plate suddenly and completely with a sharp report. Figure 20 (*J*, *K*, and *L*) are failures which are occasionally found in laminated plates. The plate shown in Figure 20 (*K*) separated completely at a large lamination without transverse fracture of either plate or weld metals. The T-member shown in Figure 20 (*L*) contained a lamination which separated without failure of plate or weld metals.

V. DISCUSSION

Because of the large number of specimens and the number of different conditions under which the tests were conducted, a statistical method of evaluation of the data was deemed desirable. The number of specimens tested under each condition was small, only four. The rating method was based on a consideration of all of the conditions rather than on a large number of results from any one given condition. Several factors were either measured or noted during the investigation, and these were believed to have contributed to the welding quality of a steel to different extents. The final weighted rating then had to contain a consideration of all contributing factors.

During the course of investigation, several steels were eliminated from further consideration because of early failures or because of some other factor. These steels are not considered in the rating charts given below, but are discussed in section VI.

In tables 14 and 15 are summarized, for the as-rolled and the normalized conditions, respectively, the ratings and rank numbers derived in the preceding tables from the various measurements and observations of the T-bend tests. The weighted rank calculated from a combination of the various rating factors is also given. The data in the upper part of each table are the averages of the 17 test groups for all combinations of welding and testing temperatures. In the lower part of the tables, the data represent the single test groups of four specimens for each plate thickness, which were welded and tested at room temperature.

The second column in each table gives the weighting factor assigned to each basis of rating shown in the first column. These weights

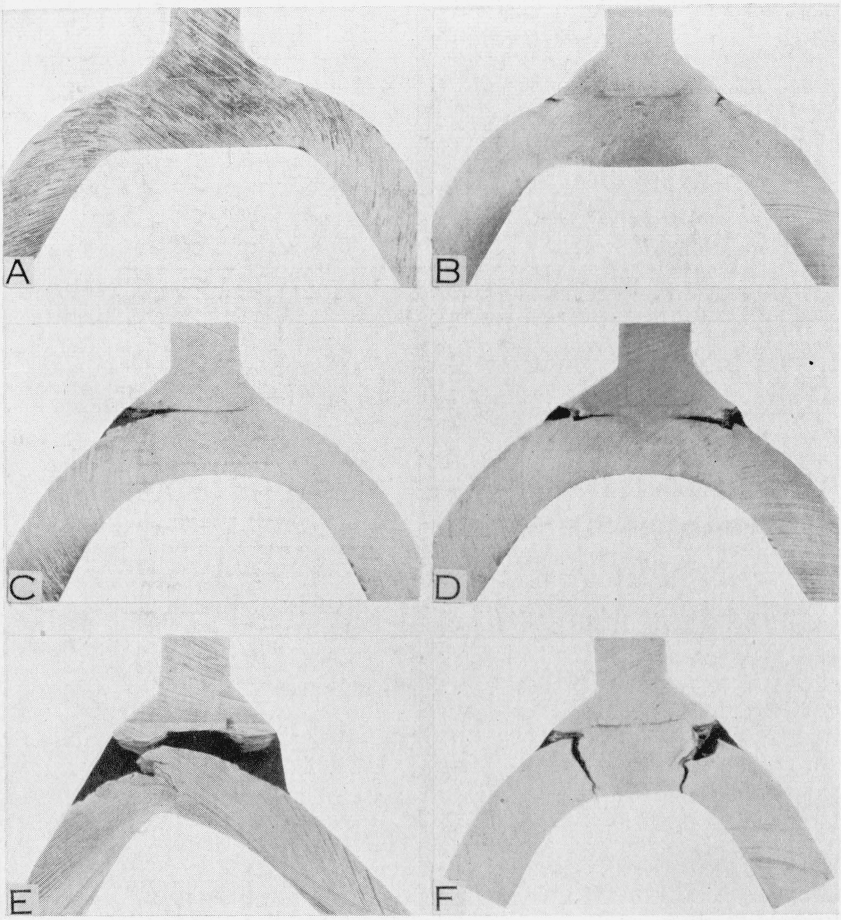

FIGURE 19.—*Typical fractures of T-bend specimens.*

A, No failure. *B*, Slight bond failure, both sides; type I fracture. *C*, Complete bond failure, following line of fusion; type I fracture. *D*, Bond failure, complete; gradual failure along heat-affected zone; type I fracture. *E*, Bond failure, complete, both sides; plate failure, two-thirds, originating in bond; types I and II fractures. *F*, Plate failure, complete, both sides; started as bond failures, then turned into plate; type II fracture.

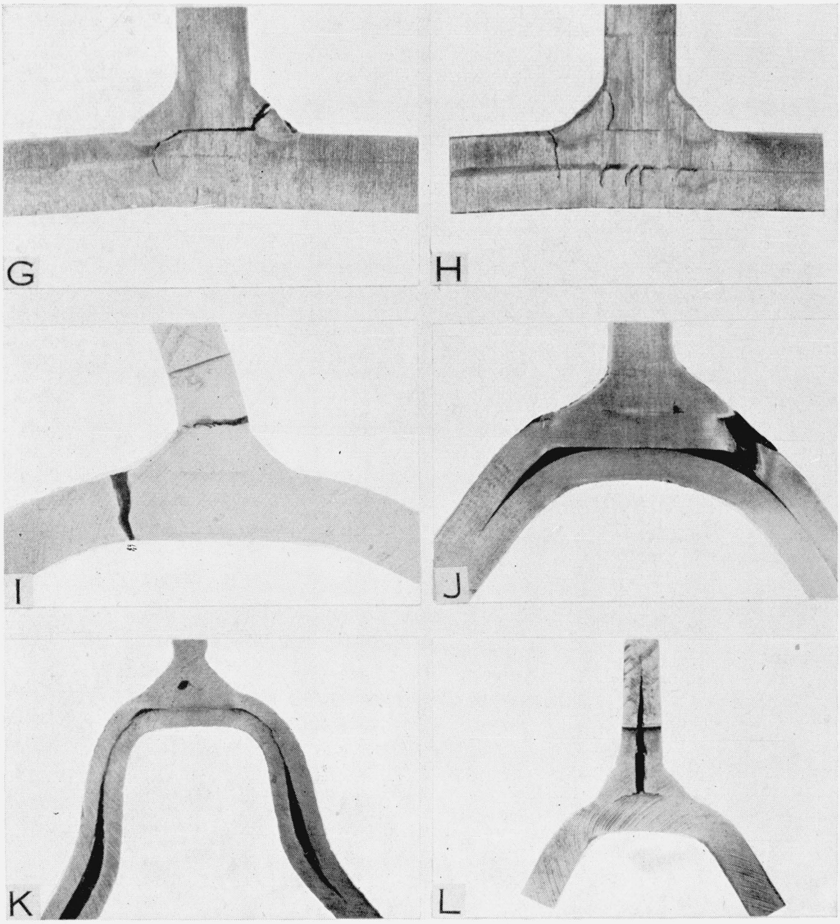

FIGURE 20.—*Typical fractures of* T-*bend specimens.*

G, Weld failure, complete through blowhole; plate failure, two-thirds, sharp under opposite fillet; type III fracture. *H*, Plate failure, one-half, sharp; bond failure complete along tongue of specimen; type III fracture. *I*, Plate failure, complete, sharp; tongue broken by impact at failure of plate; type III fracture. *J*, Plate failure, one-half, laminated plate, failed by separation of laminations. *K*, Laminated plate, failed by separation and buckling without transverse cracking. *L*, Stresses relieved by opening of lamination in tongue; no failure in plate metal, bond zone, or weld metal.

were adjusted so that the sum of the weighting factors for each plate size would equal 10, allowing a maximum possible weighted rank of 100, since the highest rank number is also 10. The sum of the weighting factors for all sizes combined was made equal to 50, by assigning appropriate weights to the averages of the various ratings for all thicknesses of each steel.

The largest weight was given to the ratings based on the angle at maximum load, which is the most accurate of the measurements in the T-bend tests, and probably the most significant, since any kind of failure at a small angle of deflection resulted in a low angle at maximum load. Two ratings are based on this measurement: (1) the average angle, and (2) the average deviation below 60° of the angle measurements for individual specimens. This latter rating assigns a lower rank to steels for which the angle at maximum load was below 60° for any individual specimen, thus penalizing nonuniformity as well as a low average angle.

The percentage of plate failures was given less weight, because the angle of deflection at failure is a factor which was not considered. This angle was recorded in most of the tests, but it could not be determined accurately in the low-temperature tests, where the specimen was immersed in liquid; and even in the tests at room temperature the determination of the exact beginning of the failure, which was often very gradual, depended largely on the opinion of the observer. At times the beginning of the failure could not be observed, particularly if it started at the back of the specimen on the side opposite to the observer.

Failures in the bond or weld metal were not considered separately in this determination of the weighted rank, because they do not depend entirely on the character of the plate metal. These failures appeared to be more or less of a residual type, that is, specimens which did not fail in the plate metal often failed in the bond or weld at high angles of deflection. However, a failure in the bond or weld relieved internal stresses in the specimen, and thereby tended to reduce the probability of a plate failure. Therefore, the rating on all failures, which includes both plate failures and bond or weld failures, was given a small weight in the determination of weighted rank.

The smallest weight was given to the rating based on the measurement of maximum load. A high maximum-load rating would appear to be desirable for welded structures, but frequently a high load rating was associated with a low angle at maximum load in brittle steels, resulting in sharp, complete failures of the plate metal. The maximum-load measurements are not particularly significant, except for comparing specimens cut from the same plate, since this load is approximately a function of the cross-section area of metal at the joint, which could not be measured accurately because of slight variations in size and shape of the weld fillets. This effect cannot be evaluated by ordinary or simple measurements. For these reasons, the rating based on the maximum load was given only a small weight, and was included mainly for the purpose of making the summary complete, rather than for its effect on the total weighted rank.

In the body of each table (14 and 15), the first two columns under each steel number in the heading show the rating and the rank number for each of the rating factors, taken from the preceding tables. The weighted rank in the third column is obtained by multiplying the rank number by the weight assigned in the second column of the table.

The numbers in parentheses at the bottom of each section of the table give the relative order of merit of the six steels, as determined by the total weighted rank for all thicknesses combined.

A summary at the right of each table gives the highest and the lowest values of the several ratings and rank numbers of each steel.

The method of determination of the weighted rank can perhaps be best explained by taking one steel as an example and following it through each of the steps necessary to determine the weighted rank. Steel 139, as-rolled, is the example used. The summary of ratings and the rank numbers for this steel, and the weighted rank determined from these rank numbers, are found in the fourth, fifth, and sixth columns in the upper portion of table 14. The fourth column gives for each basis of rating indicated in the first column the rating for each size and in most cases for all sizes combined. The fifth column gives the rank number associated with each rating. The rating and rank numbers are taken from tables 8, 9, 10, 11, and 13. The sixth column gives the weighted ranks as obtained by multiplying the rank numbers by the weighting factor shown in the second column of table 14.

The first basis of rating considered is the average angle at maximum load, for all specimens tested in each plate thickness and including all combinations of welding and testing temperatures. The ratings and rank numbers for angles of bend at maximum load are found in table 9. The average angle at maximum load for all combinations of welding and testing temperatures (abbreviated: "av. all temperatures" in table 9) of ¼-in. thicknesses of steel 139 AR was 59°. From the section for determination of rank at the bottom of table 9, it is found that an angle of 59° corresponds to a rank number 4. Similarly, for the ½- and ¾-in. thicknesses with angles of 56° and 63°, respectively, the rank numbers are 2 and 6. For all sizes combined, specimens welded and tested at all temperatures (the column at the right of table 9,) the average angle is 59.3° and the rank number, 4.

In table 14, the weighted ranks (column 6) for the ¼-, ½- and ¾-in. thicknesses are found to be 12, 6, and 18, respectively. These were found by multiplying the respective rank numbers (determined as explained above in table 9) for each thickness by the weight factor 3. For all thicknesses combined, the rank number 4 is multiplied by the weighting factor 6, yielding 24 as the weighted rank. The sum of these four weighted ranks is 60, which may be compared with the values 27, 105, 75, etc. derived in a similar manner for the other steels.

The rating and rank numbers for deviations of individual angles below 60° are found in table 10. The rating numbers in this table represent the total of all deviations of angle of bend below 60° for the individual specimens, divided by the total number of specimens. These rating numbers were multiplied by 100 to eliminate decimals. It will be noted that although the data for steel 139 are incomplete, this rating is in the form of an average for the specimens tested and the rating would not be affected except insofar as the average of the missing specimens might differ from the average of the specimens tested. The weighted rank for deviations was obtained in the same manner as that for average angle.

The percentage of plate failures is given in table 11, and the rank numbers were taken from the tabulation at the bottom of this table. A summary of plate failures and rank numbers is given also in table 13. For plate failures, a weighting factor of 2 was used for each thickness and of 6 for all thicknesses combined.

The ratings for all failures in table 13 were obtained by adding the percentages of plate failures and of bond or weld failures. The rank numbers for all failures were determined from the tabulation of range subdivisions at the bottom of this table. A weight of 1 was used for calculation of the weighted rank for each thickness and a weight of 2 for all thicknesses combined.

For maximum load, the values in the "rating" (fourth) column represent the average maximum load, in pounds, of all specimens (in all combinations of welding and testing temperatures). These averages are given in table 8, and the rank numbers were obtained (separately for each thickness of plate) from the summary at the bottom of this table. A weight of 1 was assigned to the maximum load for each thickness; and since the average maximum load of all sizes combined has no particular significance, no rating was given in this case.

In the last section of the upper portion of table 14 are given the total weighted ranks for each thickness, for all thicknesses combined, and for the grand total. The total for each thickness is found by adding the weighted ranks for each of the five rating factors. For example, for the ¼-in. thickness of steel 139, the weighted ranks are: 12 for the angle, 18 for deviations, 0 for plate failures, 1 for all failures, and 2 for maximum load—a total of 33. This value may be used to compare the various thicknesses of the same steel or to compare different steels. For example, the ¼-in. thickness of steel 139 has a higher weighted rank, 33, than that of the ½-in. thickness, 18, but not so high as that of the ¾-in. thickness, 60. Therefore, the ¾-in. plate may be considered to have a better welding quality than either the ¼- or ½-in. plates and the ¼-in. plate to have a better welding quality than the ½-in. plate. Similarly, comparing the ¼-in. plates of different steels, it will be seen that steel 146 with a weighted rank of 71 and steel 144 with a weighted rank of 14 represent the extremes of the steels tested and that the welding quality decreases from steel 146, the most weldable, to steel 144, the least weldable.

The grand total (181 for steel 139) is the sum of the total weighted ranks for each of the three plate sizes and for all plates sizes combined, and is also the sum of the total weighted ranks for the five rating factors.

The value "(5)" at the bottom of the "rank" (fifth) column indicates that steel 139 was fifth in relative order of the six steels in the as-rolled condition under all combinations of welding and testing temperatures.

The weighted rank for tests at room temperature only, shown in the lower part of table 14, was calculated in a similar manner. The rating values for specimens welded and tested at room temperature are found in the tables indicated above, and the rank numbers were determined in the same manner.

Only four specimens of each plate thickness were tested at room temperature, and since this number is too small for the percentage to be significant, the ratings for plate failures and for all failures were calculated for all thicknesses combined. In these two cases, the weighting factor was adjusted so that the weighted rank for all thicknesses combined in the tests at room temperature may be compared with the total weighted ranks for plate failures and for total failures, respectively, in tests under all temperature conditions.

The data for the angle at maximum load in the room-temperature tests of the ¼-in. thickness of steel 139, as-rolled, are missing. To complete the calculation of the weighted rank, a rank number equal to the lowest rank number for the other two thicknesses was arbitrarily assigned for the angle and for the deviation, which is dependent upon the individual angles. These rank numbers are indicated by stars.

For the three other factors, the rating, rank, and weighted rank for each thickness in the tests at room temperature may be compared directly with the corresponding values for tests under all temperature combinations. Such a comparison shows that, for each of the weighting factors considered, steel 139, as-rolled, shows to better advantage at room temperature than in the low-temperature tests.

This method of analysis of data was devised to compare the welding qualities of the various steels. The steels may be directly compared by means of any one of the five rating factors, by any combination of them, or by all of them taken together, depending upon which factors may be considered to be the most important in the conduct of a test.

The summaries of the ratings and the weighted rank given in tables 14 and 15 are shown graphically in figure 21. The left half of the chart shows the weighted rank of all thicknesses combined, for each steel in the as-rolled and the normalized conditions, and for the tests at room temperature as well as at all combinations of welding and testing temperatures. The right half of the chart shows the weighted rating for each plate thickness, in both as-rolled and normalized conditions. These ratings are for the average of tests at all combinations of welding and testing temperatures. Tests made at room temperature only are not considered for each thickness separately, because only a small number of specimens was tested.

The several components of the weighted rating are indicated by different shadings of the bars, and the relative weight assigned to each factor is shown in the legend at the bottom of the chart.

In table 14, the upper portion is devoted to welds made and tested at all temperatures while the lower portion contains results of tests of steels welded and tested at room temperature only. For steels welded and tested at all temperatures, the values, last line, for total weighted rank range from 121, for steel 144, to 336 for steel 146. For steels welded and tested at room temperature only, the total values range from 143, for steel 144, to 430 for steel 146.

The values for all steels are higher under room-temperature conditions than under lower temperature conditions except for steel 150, which was slightly lower in the room-temperature tests. This indicates that welding and testing at low temperatures caused a decrease in the bending properties of welded steels. Steel 150, which contained approximately 2 percent of nickel, might be expected to have good bending properties at low temperatures because of the well-known beneficial effect of nickel on the physical properties at subnormal temperatures. However, other steels also contained nickel in about the same amount, and these had decidedly lower bending properties at low temperatures than at room temperature. Closer examination of the data for the individual thicknesses of steel 150 indicates, however, that for the ¼- and ½-in. plates, the average angles were higher and the deviations below 60° were lower at room temperature than at

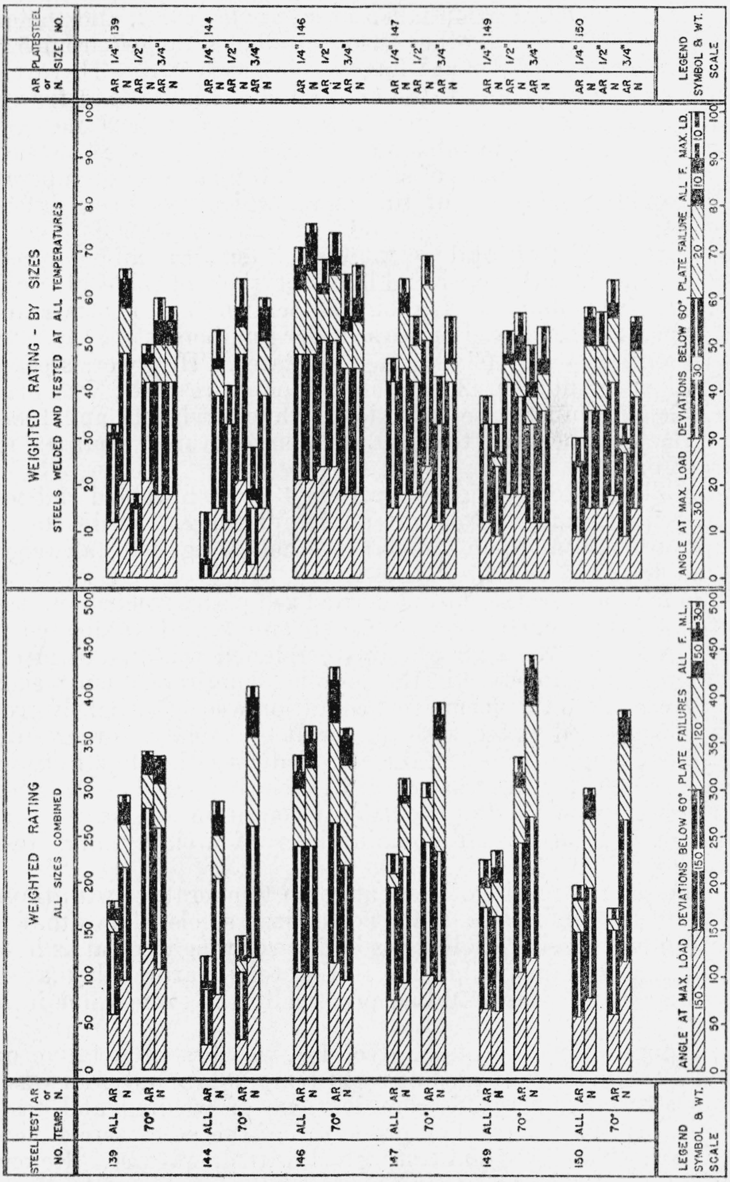

FIGURE 21.—*Weighted ratings of steels.*

lower temperatures. Calculation of the weighted rank for the individual thicknesses in the tests at room temperature (not shown in the table) showed that in the ¾- and the ¼-in. thicknesses, the weighted ranks for tests at room temperature were higher than for tests at all temperature combinations. For the ¾-in. thicknesses, however, the weighted rank was much lower, and this thickness alone lowered the weighted rank of all sizes combined, in the tests at room temperature. The low rank for the ¾-in. specimens tested at room temperature was due to the extremely low angles at maximum load. One specimen containing a plate lamination failed at an angle of 35°, and the angle at maximum load for the other three specimens ranged from 52° to 57°, an average of 50° for the four specimens tested. There was a wide and erratic variation of the angles at maximum load for specimens of this steel tested at other combinations of welding and testing temperatures, as shown in table 9 and in figures 13 and 14. The low rating of the ¾-in. specimens of steel 150 in tests at room temperature was due to nonuniformity of this steel, which has been discussed previously.

The relative order of total weighted rank (small numbers in parentheses, last line of both upper and lower portions of table 14) differed considerably for tests made at room temperature and for those made at all temperatures. Based on these order numbers, steel 146 ranked first and steel 144 last (sixth) in both cases. However, steel 139, which had order number 2 in room-temperature tests, was fifth in tests under all temperature conditions, while steels 147 and 150 had lower order numbers in tests at all temperatures than at room temperature.

Steel 146 had a total weighted rank of 430 when welded and tested at room temperature and 336 at all temperatures. Only steel 139 welded and tested at room temperature had a higher total weighted rank than steel 146 at all temperatures.

Results for the specimens from normalized plates welded and tested in all temperature conditions (table 15 and fig. 21) indicated that the total weighted rank for all sizes combined was higher in every case than for the same steel in the as-rolled condition. The weighted rank for steel 149 in the normalized condition was only slightly greater than in the as-rolled plates, with the result that relative order number of this steel dropped from 3 in the as-rolled condition to 6 in the normalized. Except for this difference, the relative order numbers of all steels were the same in the normalized condition as in the as-rolled condition for tests at all combinations of welding and testing temperatures.

A comparison of results of tests at room temperature with those at all temperature combinations, for normalized steels, shows that with the exception of steel 146, all steels had lower weighted ranks in tests at all combinations of welding and testing temperatures than at room temperature only. Steel 146 had practically the same value in both cases.

In the normalized condition, steel 149 was first in relative order for material welded and tested at room temperature only but was last for tests at all temperature combinations of welding and testing. This indicates that the bending properties of this steel were adversely affected by both welding and testing at low temperatures. Reference to figures 13, 14, 17, and 18 indicates that the lower number for this steel at all combinations of welding and testing temperatures was due mostly to the behavior at the low testing temperatures, although in the ½-in. thicknesses there was a definite decrease in the angle at maximum load and an increase of plate failures, at low welding temperatures. There may be some relation between low order numbers for this steel at low testing temperatures and the unusually small improvement of welding properties on normalizing. There was nothing unusual in the tensile or hardness properties, or in the changes of these properties on normalizing, to indicate that the change of welding quality on normalizing should be different than for the other steels. The tensile properties at low temperatures were not measured. It may be significant that this steel was the only one containing a large amount of phosphorus.

A comparison of the ratings in the as-rolled and the normalized conditions for tests at room temperature only (tables 14 and 15 and fig. 21) indicates that steels 139 and 146 had lower weighted ranks in the normalized condition. The weighted ranks for all other steels were higher in the normalized conditions than in the as-rolled conditions, much higher in steels 144 and 150. Since the ratings of the normalized steels welded and tested at room temperature were all comparatively high and cover only a limited range, the relative order is not of particular significance.

The lower rating of normalized steel 146, in room-temperature tests, is due in large part to the low rating of the ¼-in. thickness, caused by a bond failure of one of the four specimens at an angle of 40°. Since this steel was quite uniform, the low angle for this specimen was probably due to a weld defect.

The rating for the tests at room temperature for steel 139, as-rolled, may be too high, because some of the data were incomplete and the method of computing the angles was changed after the first few tests.

The ratings for steel 144, as-rolled, were consistently much lower than the ratings for the normalized condition. This obtained for all thicknesses and for tests made at low temperatures as well as at room temperature. This steel had considerably lower yield point and tensile strength in the normalized than in the as-rolled condition, indicating a considerable amount of rolling hardening. It would appear, therefore, that the considerably larger weighted rank for steel 144 normalized was due to actual improvement of welding quality by the normalizing treatment. This steel had many manganese sulfide inclusions and was the "dirtiest" of the six steels.

The low rating of steel 150, as-rolled, in room temperature tests has been attributed, previously, to nonuniformity of the steel. In the normalized condition, the angles at maximum load were considerably higher and more uniform than in the as-rolled condition, indicating that the plates were made more weldable by the normalizing treatment.

The relative order of the steels in each thickness and condition and the total weighted ratings of the different thicknesses and conditions of treatment for each steel are shown more clearly in the upper part of figure 22. The left half of the chart shows the comparative ratings of the various sizes of each steel for the as-rolled and the normalized conditions, and on the right half is shown the effect of normalizing the plates before welding. In each column of the chart, the steel numbers are shown opposite the respective ratings for the size and condition indicated in the column heads, and lines are drawn to connect the corresponding steel numbers in each of the columns which are to be compared. The average for the six steels is given in each column, and these average values are connected by dotted lines.

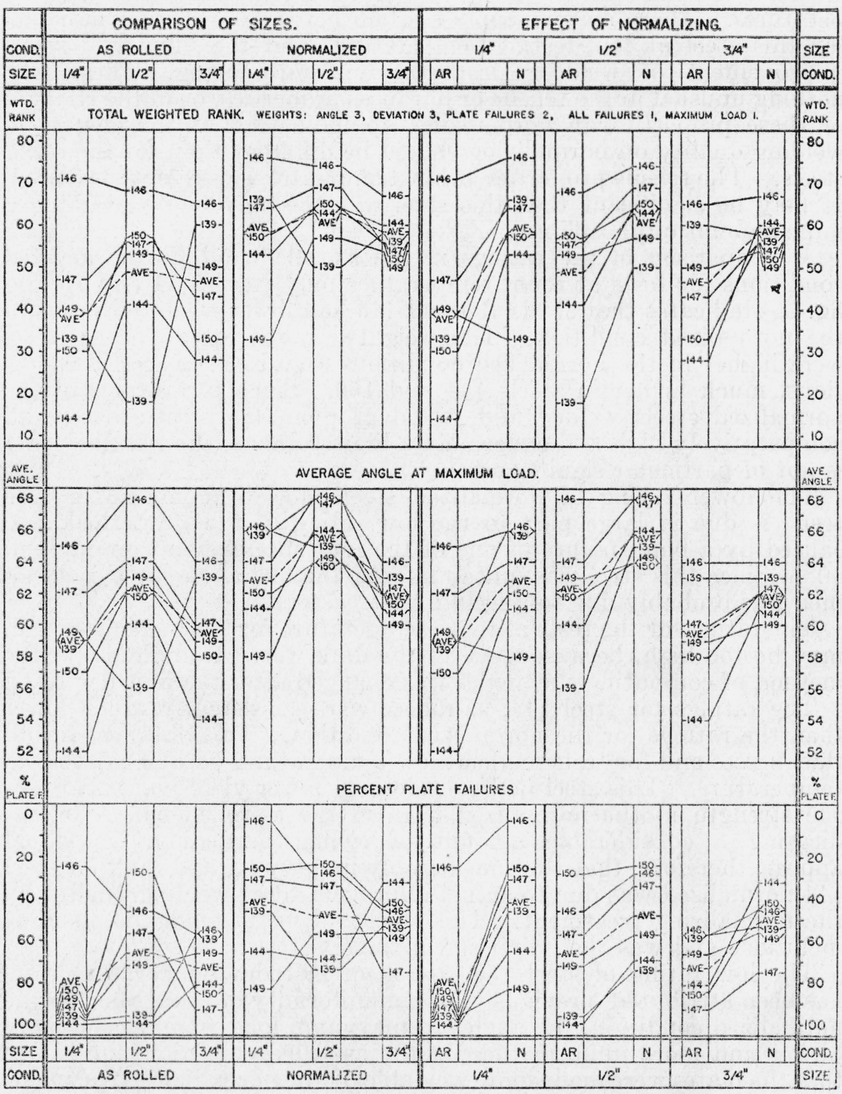

FIGURE 22.—*Comparison of ratings and methods of weighting.*

Steels welded and tested at all temperatures.

The comparisons between the different thicknesses of plates show that for most of the steels the highest ratings were found in the ½-in. thicknesses, in both the as-rolled and the normalized conditions.

An attempt was made to find a relation between the ratings for each thickness of each steel and the depth of heat penetration in the plate. The maximum penetration was measured on macrographs of the specimens welded at room temperature. There was no correlation between the maximum heat penetration and the ratings for tests made at any temperature.

The effect of normalizing as measured by the weighted rank is shown in the right half of figure 22. In all cases except two, the weighted rank for the normalized plates of one size of a steel is higher than for the as-rolled plates. It is noted also that steels having the lowest weighted ranks in the as-rolled condition showed the greatest improvement after the normalizing treatment. The ¾-in. plates of steel 139 and the ¼-in. plates of steel 149 are two exceptions which have a decrease of weighted rank after normalizing. The ½- and ¾-in. plates of steel 149 increased less in rating after normalizing than the average for the other steels. The fact that for each size of this steel the improvement of weighted rating on normalized plates was less than for the other steels tested (one thickness actually showed a decrease) substantiates the finding, previously discussed, that the average rating for all sizes combined showed a very low increase on normalizing, and indicates that this was inherent in the steel itself and was not a function of size or an accidental fluctuation. From table 2, it is noted that the physical properties of this steel were very similar in both the as-rolled and normalized conditions, indicating that this steel may have been normalized at the mill prior to shipment.

The normalized ¾-in. plates of steel 139 had lower ratings than the as-rolled plates, while the normalized ¼- and ½-in. plates had considerably higher ratings. This would indicate that the behavior of the ¾-in. plates was abnormal.

Figure 22 also shows the ratings of the steels, based on the average angle at maximum load and on the percentage of plate failures. The scale for the rating on the basis of percentage of plate failures is reversed, so that the steels in which there were few plate failures appear near the tops of the columns. These ratings serve as a check on the validity of the ratings based on the weighted rank. The relative order of the steels (reading from top to bottom in the columns) and the curves indicating the changes of rating with size and with normalizing are about the same in all sections of the figure. A study of the curves and of the relative order of the steels shows that, while the ratings based on the average angle at maximum load and on the percentage of plate failures, respectively, do not agree in every detail, there is substantial evidence that a close relation exists between the angle at maximum load and the number of plate failures.

Plate failures had more effect on the angles at maximum load than bond or weld failures because: first, bond failures were residual failures which usually occurred at angles greater than the normal angle at maximum load; and, second, the cross section of the specimen was not reduced to any great extent, although the reinforcing effect of the weld fillet was partially eliminated.

The ratings based on the weighted rank are weighted averages of all of the measurements obtained in the tests. The weights, shown in the heading of the upper section of figure 22, were arbitrarily assigned for reasons previously discussed. Since the largest weights were given to the angle at maximum load and to the deviations below 60°, the ratings based on the weighted rank should agree closely with the ratings based on this angle. This is evident in the two upper sections of figure 22. Differences may be explained as the effect of the plate failures on the weighted rating, as shown in the lower section of the figure. The other factors in the weighted rating, namely, all failures (including plate failures and bond failures), and maximum load, were given small weights, and their effect on the weighted rank is almost negligible, as can be seen by comparing the three methods of rating shown in figure 22.

A brief summary, using the order numbers, which is based on all five factors and all thicknesses, is given in table 16.

TABLE 16.—*Order numbers of welded steels*

Order number	Steel number			
	As-rolled		Normalized	
	Room temperature	All temperatures	Room temperature	All temperatures
1	146	146	149	146
2	139	147	144	147
3	149	149	147	150
4	147	150	150	139
5	150	139	146	144
6	144	144	139	149

Steel 146 was first for all conditions except when welded and tested in the normalized condition at room temperature, where its order was fifth. However, a further analysis indicated that values of total weighted rank of this steel did not decrease under these conditions, but were approximately the same. However, the welding quality of other steels, notably 144, was appreciably improved if the plates were welded in the normalized condition. It would appear therefore that the welding quality of steel 144 was appreciably influenced by normalizing. Evidence of this is shown in figures 23 and 24, photographs of ½-in. plates welded and tested at room temperature in the as-rolled and normalized conditions, respectively. When tested in the as-rolled condition, all specimens failed in the plate metal (four type III fractures), with sharp reports. The average angle at maximum load was 56°. Specimens from the plate normalized before welding bent to the limit of the jig without failure and with an average angle of 68°.

Summarizing, for all tests the order was as follows: 146, 147, 149, 150, 139, 144.

To determine whether changing the method of weighting would appreciably affect the relative order of these steels, other methods of weighting are compared in table 17, together with a summary of the weighted rank, by sizes for each of the methods of weighting.

It is evident that the method of weighting has little effect on order numbers in corresponding positions in the different sections of the table. In only one case is the order number changed by more than two places; and in all cases except one, the highest and the lowest order numbers occupy the same position. Three of these four methods are compared graphically in figure 22.

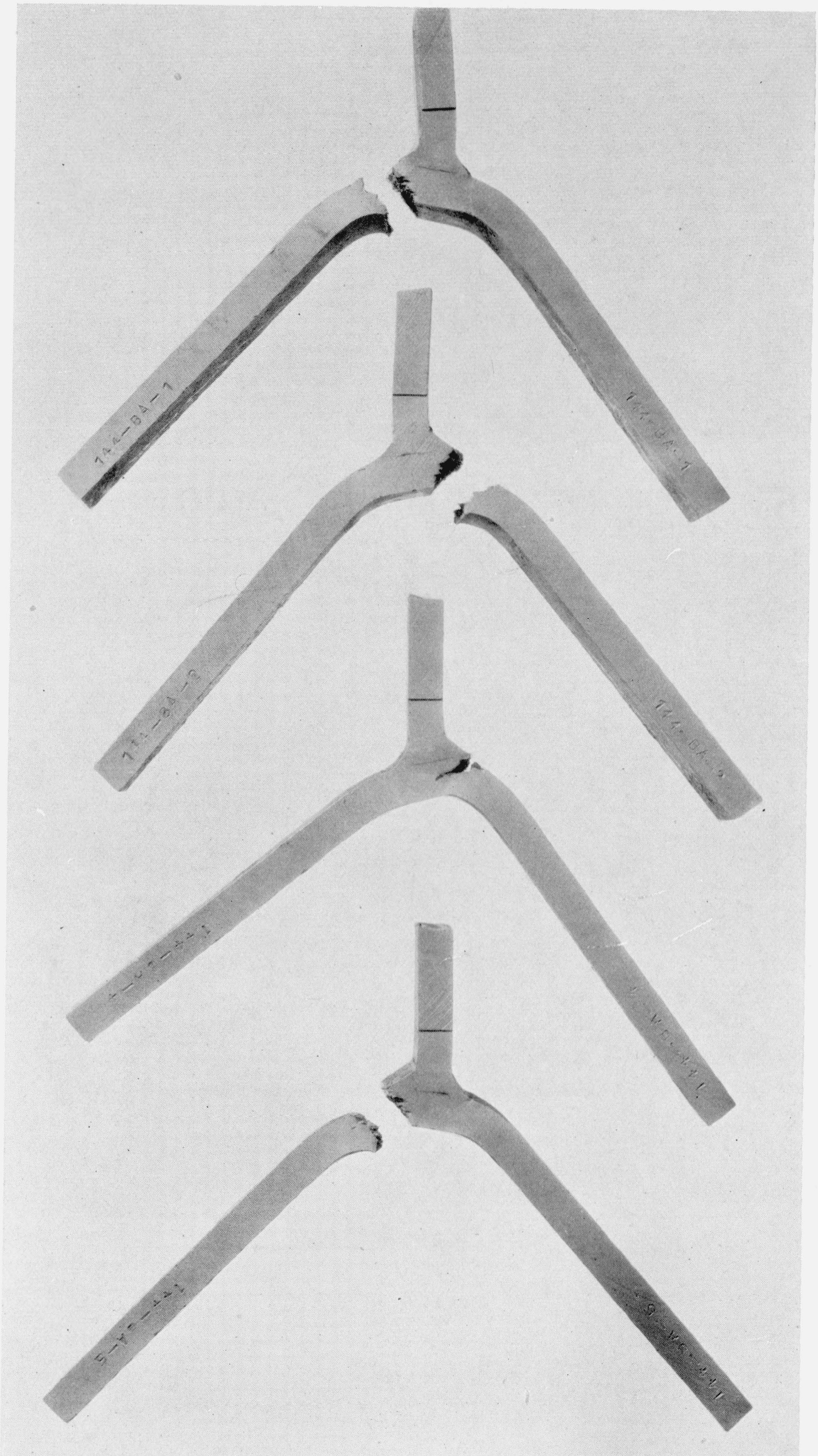

FIGURE 23.—*Steel 144, ½-in. plates, welded as rolled.*

Sharp fractures in the plate metals. Average angle at maximum load, 56°.

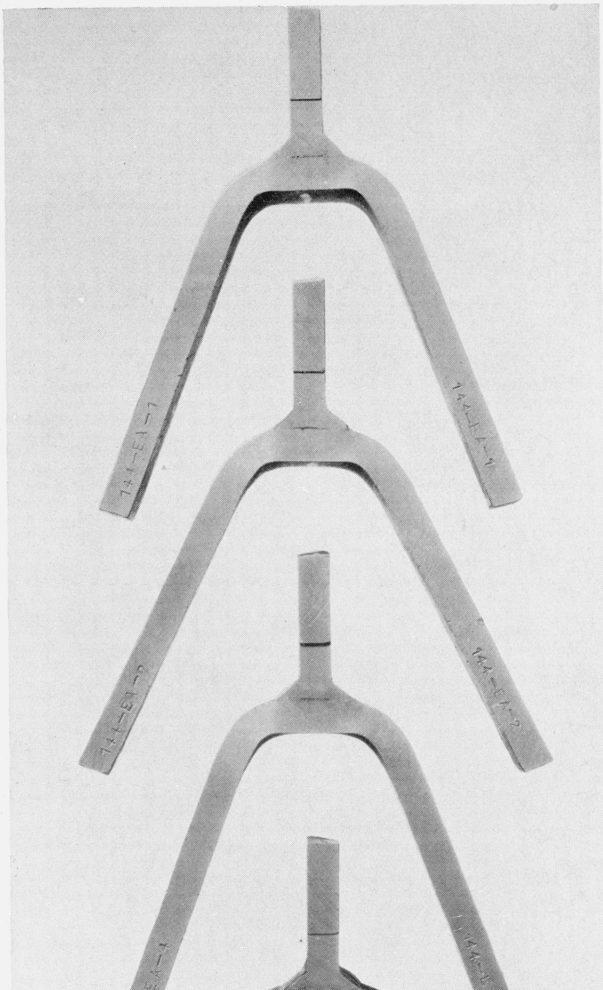

FIGURE 24.—*Steel 144, ½-in. plates, welded after normalizing treatment*

No failures. Average angle at maximum load, 68°.

TABLE 17.—*Comparison of weighted rank by sizes, for various methods of weighting*

[Steels welded and tested at all temperatures]

Steel	¼ in.		½ in.		¾ in.		As rolled		Normalized		AR & N Comb.	
	AR	N	AR	N	AR	N	Total	Order	Total	Order	Total	Order
TOTAL WEIGHTED RANK (Weights: Angle 3, Deviation 3, Plate Failures 2, All Failures 1, Max. Load 1)												
139	33	66	18	50	60	58	111	5	174	5	285	5
144	14	53	41	64	28	60	83	6	177	4	260	6
146	71	76	68	74	65	67	204	1	217	1	421	1
147	47	64	56	69	43	56	146	2	189	2	335	2
149	39	33	53	57	50	54	142	3	144	6	286	4
150	30	58	57	64	33	56	120	4	178	3	298	3
Total	234	350	293	378	279	351	806		1,079		1,885	
Order	6	3	4	1	5	2						
RANK FOR ANGLE, DEVIATION, AND PLATE FAILURES ONLY (Equal Weights)												
139	10	21	5	16	18	18	33	5	55	4	88	4
144	1	16	11	19	6	19	18	6	54	5	72	6
146	23	25	22	24	19	20	64	1	69	1	133	1
147	14	21	18	23	11	16	43	2	60	2	103	2
149	11	9	16	17	14	16	41	3	42	6	83	5
150	8	19	19	21	10	18	37	4	58	3	95	3
Total	67	111	91	120	78	107	236		338		574	
Order	6	2	4	1	5	3						
AVERAGE ANGLE AT MAXIMUM LOAD (Unweighted)												
139	59x	66	56x	65x	63x	63	59.3	4	64.7	3	62.0	3
144	52	61	60	66	54	61	55.3	6	62.7	5	59.0	6
146	65	66	68	68	64	64	65.7	1	66.0	1	65.8	1
147	62	64	64	68	60	62	62.0	2	64.7	2	63.3	2
149	59x	58x	63	64	59	60	60.3	3	60.7	6	60.5	5
150	57	62	62	64	58	62	59.0	5	62.7	4	60.8	4
Ave	590	628	622	658	597	620	60.3		63.6		61.9	
Order	6	2	3	1	5	4						
PERCENT PLATE FAILURES (Unweighted)												
139	98	46	96	74	57	53	84	5	57	5	71	4
144	100	65	99	69	81	32	93	6	55	4	74	6
146	25	3	46	28	57	45	42	1	25	1	34	1
147	97	31	57	34	93	75	82	4	47	3	64	3
149	96x	83x	72	57	66	56	77	3	64	6	72	5
150	94	26	28	24	84	44	69	2	31	2	50	2
Ave	85	42	66	48	73	51	75		47		61	
Order	6	1	4	2	5	3						

The relations between the weighted ranks and the tensile properties of the steels are shown in figure 25. At the top and bottom of the chart the steel numbers, in both conditions, are plotted against the weighted rank for each size.

There was no definite correlation between weighted rank and the yield point or the ultimate strength. The weighted ranks were apparently higher in steels with lower strengths, due largely to the abnormally high values of yield points and ultimate strengths for steel 144, which were imparted by a low finishing temperature in rolling. With the elimination of these values from consideration in the as-rolled plates, there was practically no correlation in this condition. In the normalized condition, there was no relationship whatsoever.

Also there was no definite correlation between the weighted rank and the elongation. For ¼-in. as-rolled plates, in general, the steels having the highest weighted rank had high values of elongation. However, this relationship did not exist in normalized ¼-in. plates, or in any of the ½- or ¾-in. plates.

The relations of angle at maximum load to the tensile properties are shown in figure 26. As explained previously, the angle at maximum load was assigned the greatest weight and dominates the weighted rank values. The curves in figure 26 follow very closely those of figure 25, and no good relationship was found between the angle at maximum load and the tensile properties for any of the plates.

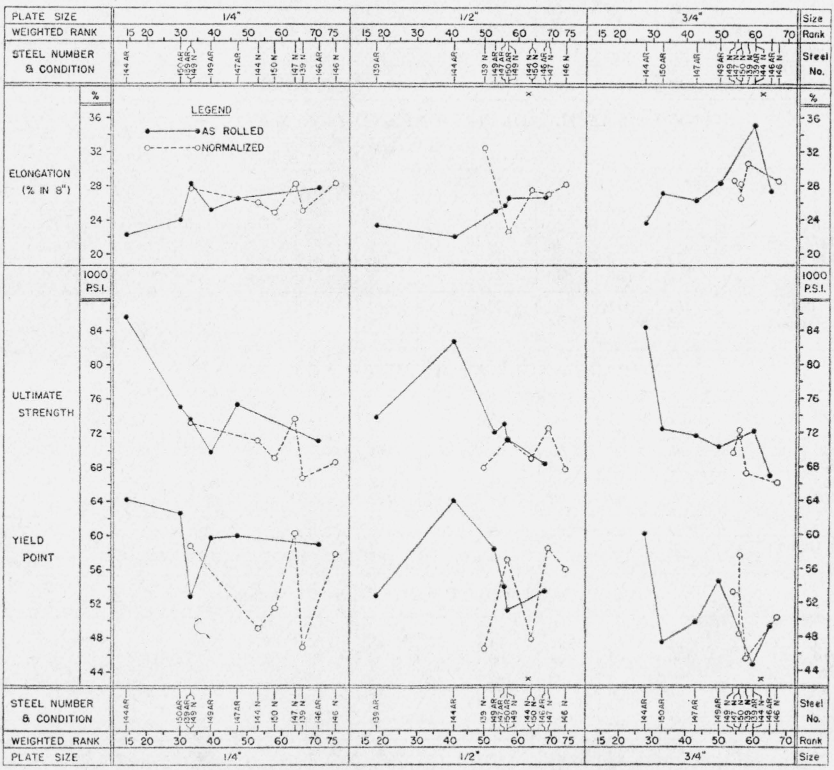

FIGURE 25.—*Relation of weighted rank to tensile properties.*

Because failures in the plates were considered undesirable, it was deemed advisable to determine whether any of the tensile properties influenced the location of the failures. The relation between the percentage of plate failures and the tensile properties is shown in figure 27. It should be noted that the scale is reversed, so that steels with the least percentage of failures (considered the most desirable) are placed at the right. It is evident that there is no definite correlation between the percentage of plate failures and any of the tensile properties.

There was an apparent correlation between weighted rank and Vickers numbers of the unwelded plates in the as-rolled ¼-in. thickness (fig. 28). There was no correlation for the normalized ¼-in. plates nor for any of the other thicknesses. There is no correlation between the weighted rank and either the highest Vickers numbers or increase in Vickers numbers. The numbers for the unwelded plates lie within a rather narrow range (145 to 180), most of them between 150 and 170. After welding, none of the Vickers numbers were high—the greatest increase in as-rolled plates being 100 in steel 144 (½-in. thickness) and in the normalized plates about 115 in steel 147 (½-in. thickness).

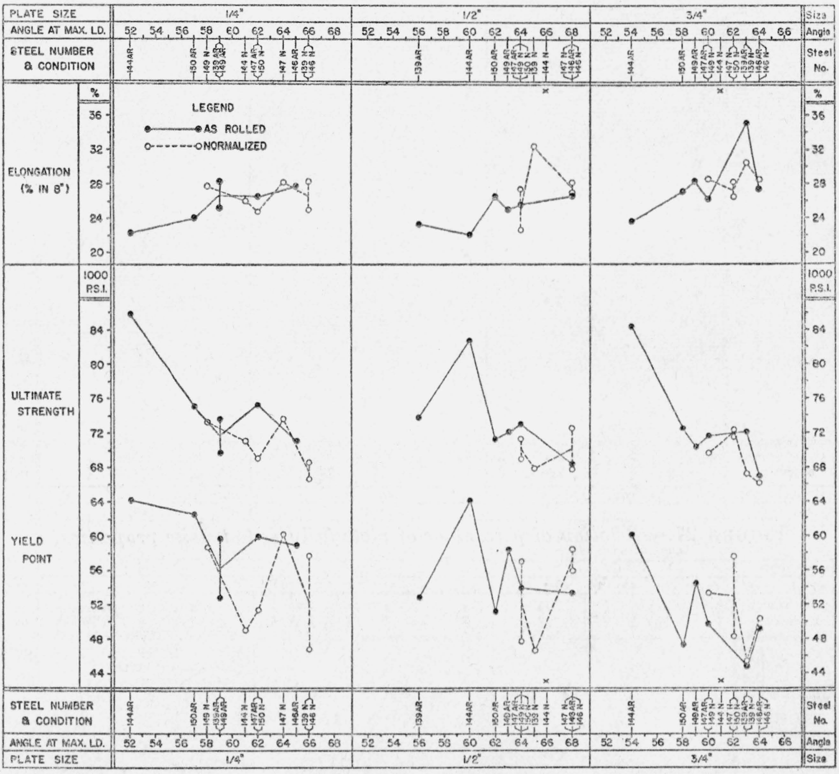

FIGURE 26.—*Relation of angle at maximum load to tensile properties.*

The relations between angles at maximum loads and Vickers numbers are shown in figure 29. It is evident that there was no good correlation in either rolled or normalized conditions.

The relations between the percentage of plate failures and Vickers numbers are shown in figure 30. There was no correlation in any thickness or condition.

Figures 31, 32, and 33 show, respectively, the relation of weighted rank, angle at maximum load, and percentage of plate failures to the chemical compositions of the plates. The percentage by weight of each of the 10 elements listed in the first column of each chart is shown for each steel and thickness. The chemical compositions of the as-rolled and normalized steels are the same, since they were taken from the same original plate, but the as-rolled and normalized steels

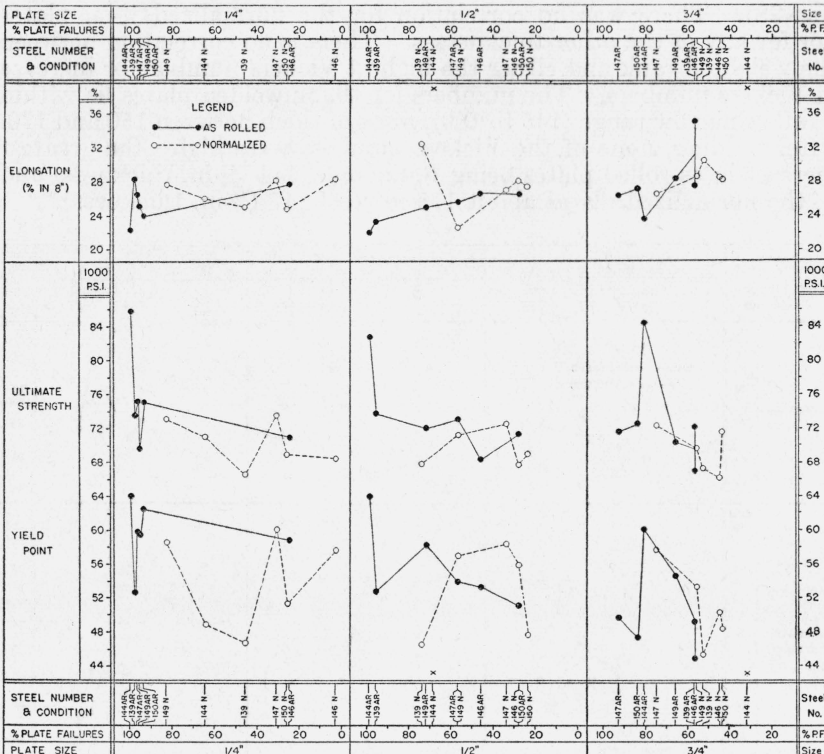

Figure 27.—*Relation of percentage of plate failures to tensile properties.*

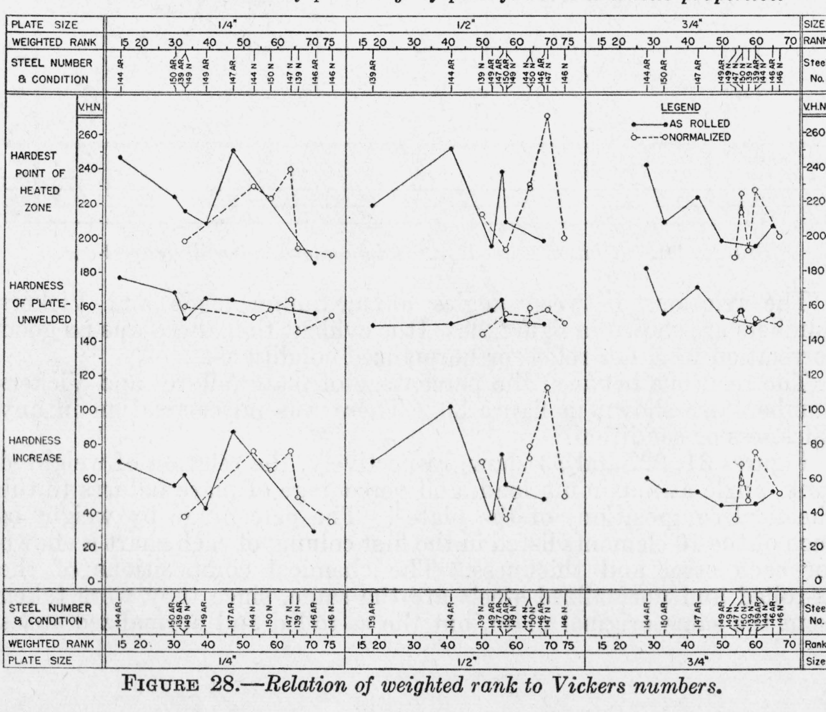

Figure 28.—*Relation of weighted rank to Vickers numbers.*

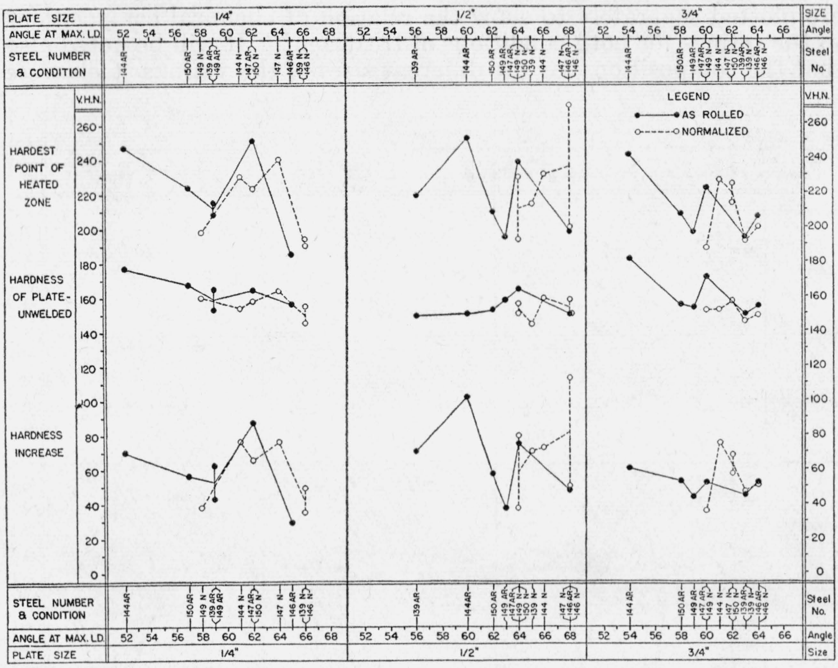

FIGURE 29.—*Relation of angle at maximum load to Vickers numbers.*

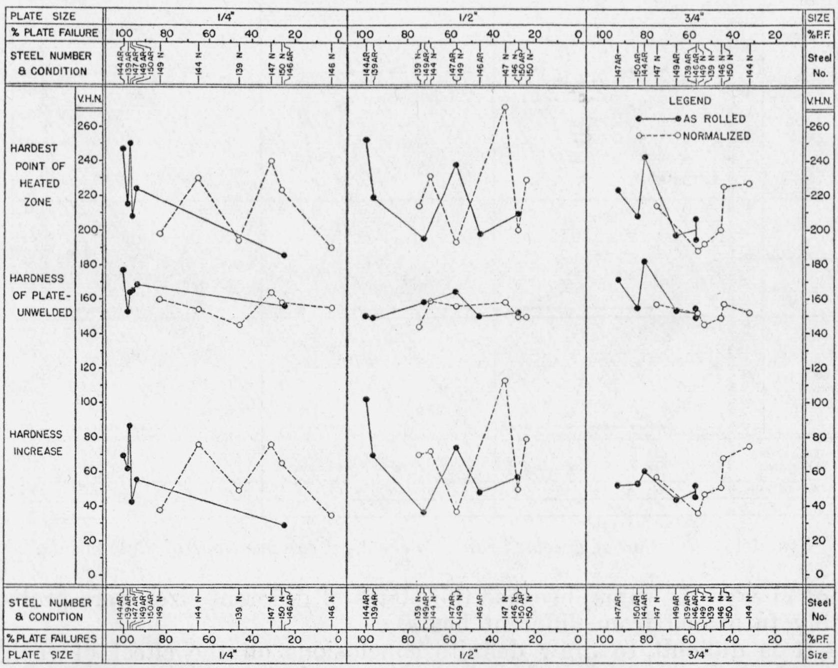

FIGURE 30.—*Relation of percentage of plate failures to Vickers numbers.*

are plotted separately to show the relation of chemical compositions to the ratings for both conditions of treatment. It will be noted also that the compositions for the different sizes of the various steels were

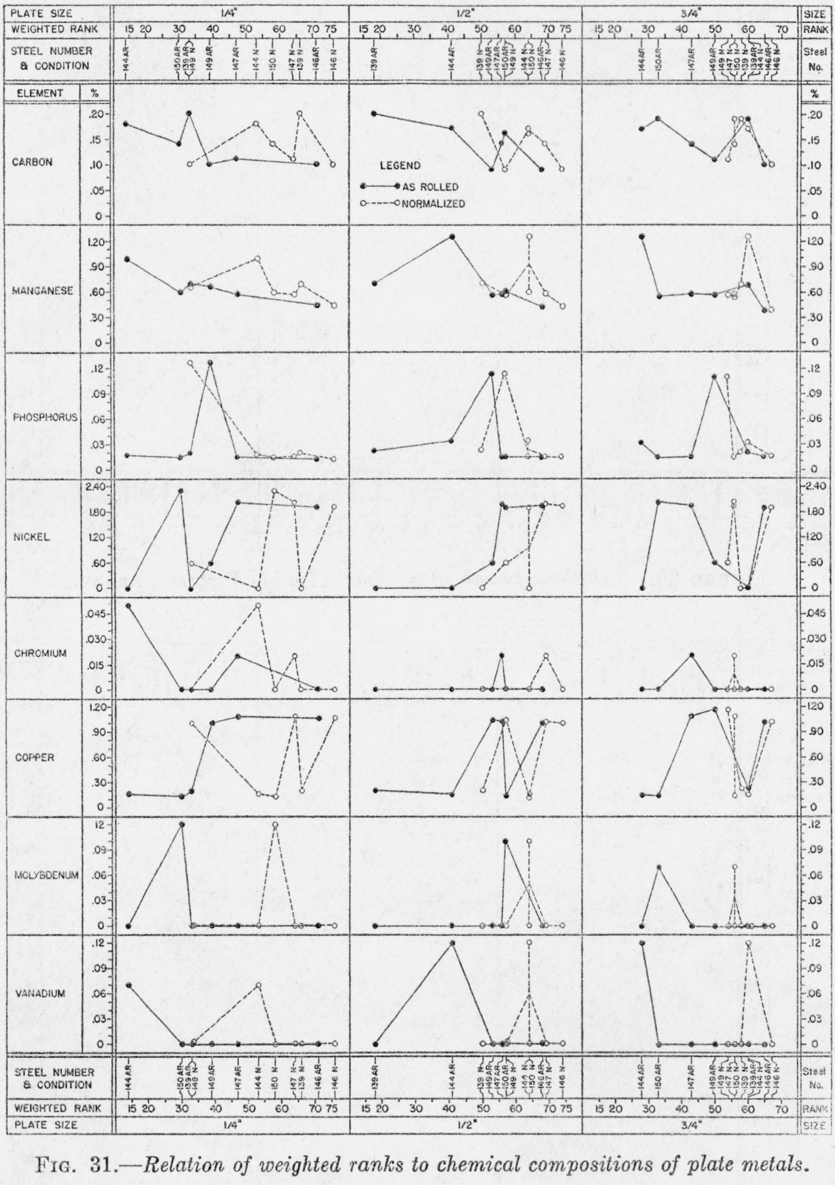

FIG. 31.—*Relation of weighted ranks to chemical compositions of plate metals.*

not always the same, because the plates of different sizes were probably furnished from different heats.

It is difficult to draw definite conclusions on the effect of each chemical element. In some steels certain elements were found only in small or insignificant amounts; in others, the effect of one element was offset or masked by one or more other elements which might have had an appreciable influence on the weldability of a steel. The

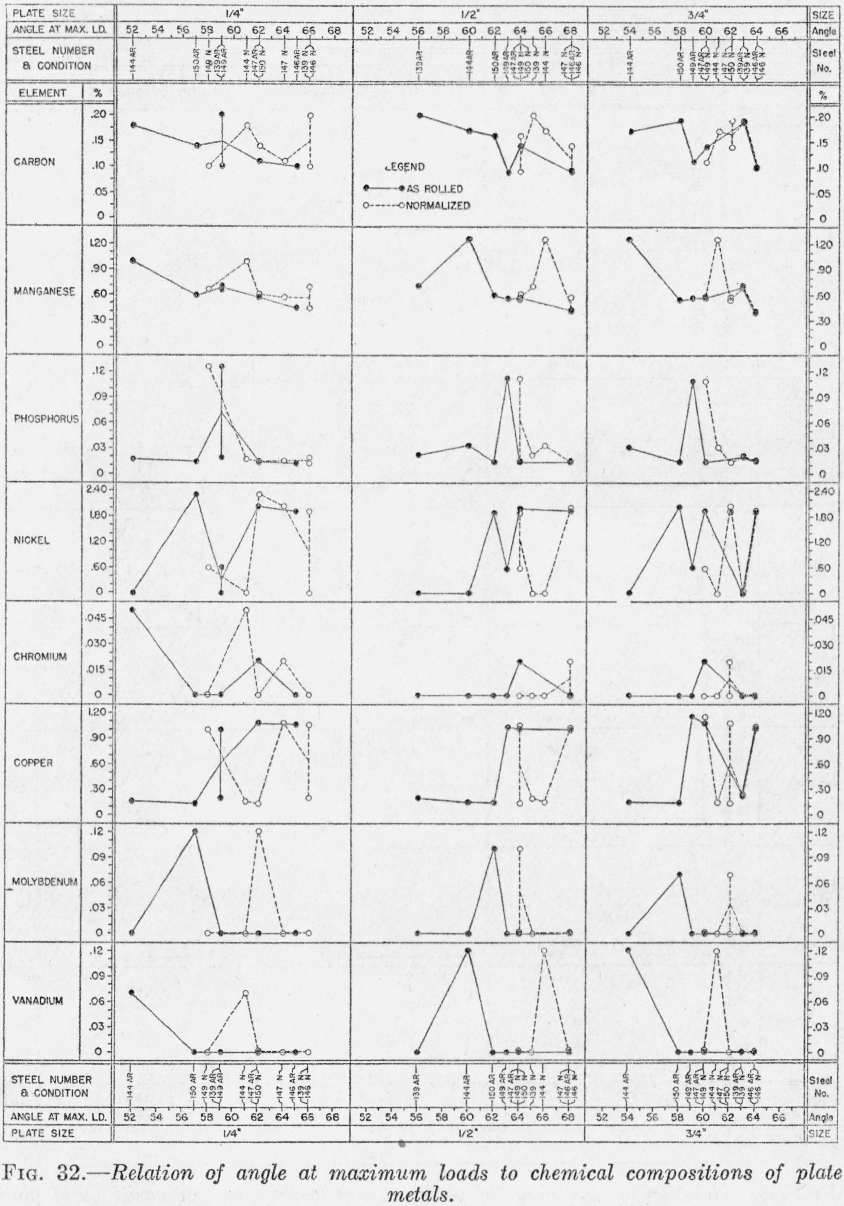

FIG. 32.—*Relation of angle at maximum loads to chemical compositions of plate metals.*

results for some steels in the normalized condition were widely different from those obtained on the same steel in the as-rolled condition, making it difficult to ascribe inferior bending properties or location of failure to a particular element. The effects of these elements are summarized below.

1. *Carbon.*—The range of carbon was 0.10 to 0.20 percent. In the as-rolled condition, the steels having less than 0.15 percent of carbon had greater angles of bend and higher weighted ranks than those having more carbon. In the normalized condition, the carbon

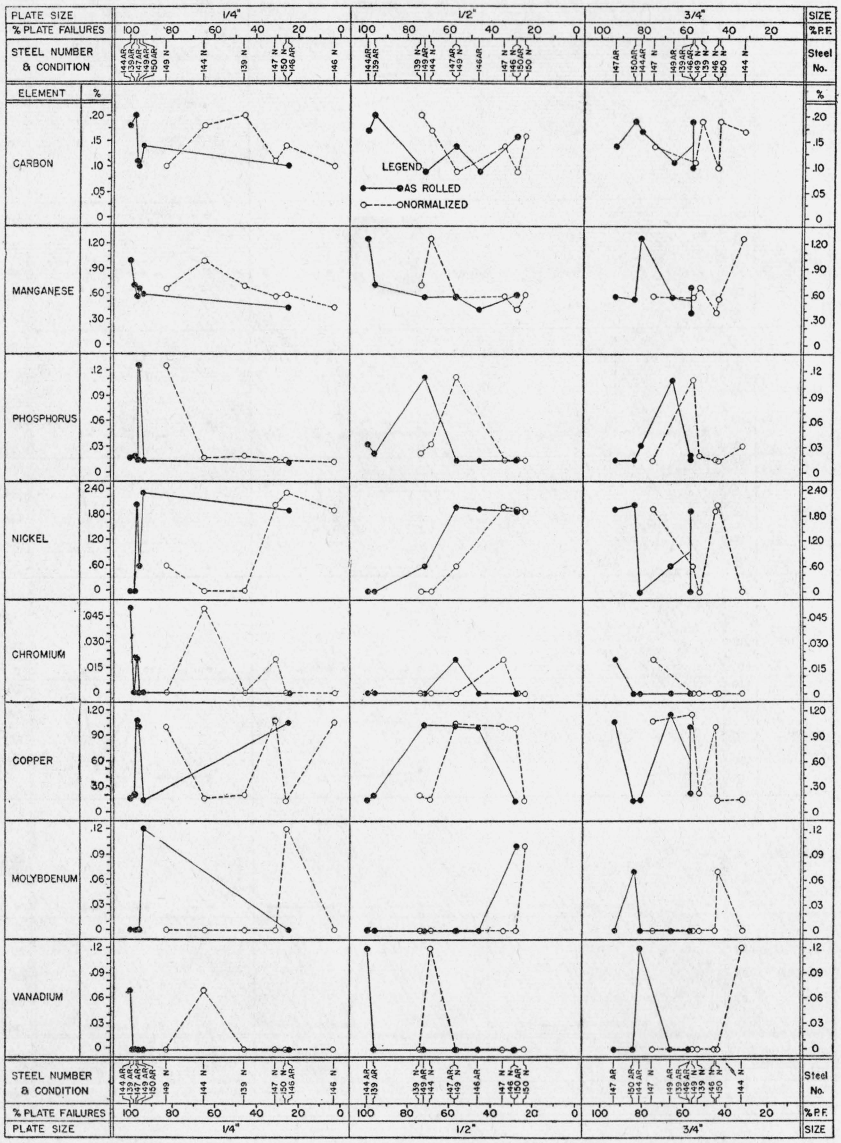

FIG. 33.—*Relation of percentage of plate failures to chemical compositions of plate metals.*

had no appreciable effect on the angle of bend or the weighted rank. Carbon had no effect on the number of plate failures.

2. *Manganese.*—The manganese did not exceed 0.70 percent except in steel 144, which in the as-rolled condition had the greatest number

of plate failures, the lowest angles of bend, and the lowest weighted ranks of any steel.

This steel was very "dirty," containing many inclusions of manganese sulfide. Usually dirty steels have poor welding quality because of discontinuities at the inclusions, which decrease the ductility, especially transversely, and prevent good cohesion between the weld metal and the plate metal. These effects are greater if the steel has been finish-rolled at low temperatures to increase the tensile properties.

It is evident from figures 31, 32, and 33 that as the amount of manganese is greater the angle of bend and the weighted rank are less and the number of plate failures is greater. This effect is less marked in the normalized condition.

3. *Phosphorus* was an alloying element in one steel, 149. Although the angles of bend and weighted rank were good, there were many plate failures.

4. *Sulfur* was present from 0.019 to 0.044 percent and in this range had no appreciable effect on the welding quality.

5. *Silicon* between 0.14 and 0.21 percent had no appreciable effect on the welding quality.

6. *Nickel* in alloying amounts was present in four of the six steels, ranging from 0.60 to 2.32 percent. Some steels with appreciable amounts of nickel had high weighted ranks and high angles of bend, others had low values. Nickel did not have an appreciable effect on the bending properties of the steels. Other elements in these steels had as much or more effect on these properties than nickel in the range of compositions investigated.

7. *Chromium* was present in such small amounts that no conclusions could be drawn as to its effect on the welding quality.

8. *Copper* in amounts of 1 percent or more was present in three steels, all of which contained nickel, and one of which, 149, contained about 0.12 percent of phosphorus. For steels 146 and 147 in the as-rolled condition the angles of bend and weighted ranks were good, but they were slightly low for steel 149. Steel 146 had the lowest percentage of plate failures of the as-rolled steels, while steels 147 and 149 had high percentages. In the normalized condition, steels 146 and 149 had about the same values of weighted rank and angles at maximum load as in the rolled condition, and steel 147 had considerably higher values. All steels had somewhat lower percentages of plate failures in the normalized condition than in the rolled condition. The high-copper steels containing nickel consistently had high values of weighted ranks and angles at maximum loads. Copper-nickel steels had good bending properties after welding. Steel 149, containing 0.12 percent of phosphorus and 0.60 percent of nickel, had bending properties somewhat inferior to steels 146 and 147, containing normal phosphorus, 1.00 percent of nickel, and 2.00 percent of copper.

9. *Molybdenum.*—Only one steel contained molybdenum. This steel also contained approximately 2 percent of nickel. In the as-rolled condition the weighted ranks and angles at maximum load were low and the percentages of plate failures high. In the normalized condition the bending properties were improved considerably and the steel was satisfactory as to welding quality.

10. *Vanadium* was found in only one steel, 144. In the as-rolled condition, there were many plate failures ana the angles and weighted ranks were low. In the normalized condition, however, there were

fewer plate failures; the angle of bend and the weighted ranks were high. The effect of vanadium may have been masked by the high manganese content. It is believed from previous tests that vanadium is beneficial in medium manganese steels.

VI. PARTIALLY COMPLETED TESTS

In addition to the six steels which were investigated completely under all of the proposed conditions of welding and testing, several other steels were investigated only in part. The complete program of bending 408 specimens for each steel required considerable time; therefore if bending tests at room temperature indicated that the welding quality of a steel was poor, no tests were made at low temperatures.

For some steels only sufficient material was furnished for the tests at room temperature and for others only the ¼- and ½-in. plates were submitted.

The reasons for not making all of the tests are as follows:

Steel	*Reason for not making all of the tests*
138	Failure to comply with requirements for tensile properties, type II fractures.
140	Failure to comply with requirements for tensile properties, type III fractures.
141	Failure to comply with requirements for tensile properties, low bending angle, type III fractures.
143	Low angle of bend, type III fractures.
145	Laminated plates, low angle of bend, type III fractures.
148	Low angle of bend, type III fractures.
157	Laminated plates, low angle of bend, type III fractures.
161	Type III fractures.
163	No ¾-in. plates, low angle of bend, type II fractures.
166	No ¾-in. plates. Failure to comply with requirements for tensile properties.
168	No ¾-in. plates.
201	No ¾-in. plates. Low bending angle, type II fractures.

The weighted ranks and order number of all specimens tested at room temperature are given in table 18.

TABLE 18.—*Total weighted rank*

[Specimens welded and tested at room temperature]

Steel	Total weighted rank and order number							
	As-rolled				Normalized			
	¼ in.	½ in.	¾ in.	Order No.	¼ in.	½ in.	¾ in.	Order No.
138		61	81	6	87	82	84	2
139		58	87	5	59	56	82	9
140		18	60	11	61	57	68	10
141	63	5	53	10	80	54	86	7
143	2	20	39	15	63	59	75	9
144	51	28	20	14	96	90	58	3
145	4	65	44	12	62	55	38	11
146	73	94	82	3	58	79	76	8
147	43	78	68	8	64	88	80	5
148	4	10	10	17	20	20	10	13
149	43	78	80	7	88	90	80	1
150	41	61	10	13	89	62	77	6
157	5	7	9	18	29	54	72	11
161	92	58	76	4	87	78	79	3
163	5	24		16	40	48		12
166	83	90		2	76	80		4
168	83	93		1	76	80		4
201	37	54		9	48	75		10

It is believed that to be satisfactory for welding, a steel should have a weighted rank of 50 in each thickness, one-half of the possible maximum weighted rank.

Steels 138, 139, 146, 166, and 168 in the as-rolled condition were the only ones which complied with this requirement. The weighted ranks of steels 147 and 149 had slightly low values for the ¼-in. plate thicknesses. Steel 141 had a value of only 5 in the ½-in. thickness. All other steels had low values in two or more thicknesses except steels 140 and 201, in which data were available for two thicknesses only.

The order numbers indicate the relative welding qualities of the steels in a manner similar to that of table 16. Two steels, 168 and 166, had higher ranks than steel 146, but these were not submitted in three plate thicknesses. Steel 166 also had low tensile strength.

For the normalized condition the weighted ranks were considerably higher than for the as-rolled condition. All steels had values of 50 or more in this condition except 145 (¾-in.), 148 (¼-, ½-, and ¾-in.), 157 (¼-in.), 163 (¼- and ½-in.), and 201 (¼-in.).

Normalizing greatly increased the welding quality of steels 144, 150, and 157. For steel 157 the weighted ranks for the ¼-, ½-, and ¾-in. plates as-rolled were 5, 7, and 9, and after normalizing were 29, 54, and 72, respectively. The tensile strength of this steel was about 85,000 lb/in.^{2} in the rolled condition and only about 64,000 lb/in.^{2} in the normalized condition, indicating that a considerable increase in tensile strength had taken place as a result of rolling. This is reflected in the low weighted rank values in the rolled condition.

Steel 144, the Navy Department's standard for construction purposes, likewise had low weighted ranks in the as-rolled condition—51, 28, and 20 for the three thicknesses. The corresponding weighted ranks for normalized plates were 96, 90, and 58. The steel also had been cold-finished in rolling to obtain high tensile strengths.

It should be stated at this point that, although the manganese vanadium steel (144) does not show to particular advantage when compared with certain other steels in this method of determining welding quality, the use of this type of steel in naval construction should not, in the opinion of the authors, be discontinued on this basis alone. Experience has shown that manganese vanadium steel is reasonably satisfactory in actual use and that its quality has improved constantly during the period of about 7 years that it has been employed. It is not considered advisable to embark on the extensive use of another type of steel until it is possible to conduct further experimentation at full scale, such as the construction of several vessels, to prove the actual advantages of those steels which show to better advantage in the present test. Current conditions preclude such experimentation, but it is hoped that after the present emergency such work may be undertaken.

Of like interest is the inconsequential improvement of steel 148. This steel was extremely dirty (fig. 1), to which poor welding quality was ascribed. Welding quality was not improved to any appreciable extent by normalizing, the weighted rank of the normalized specimens being far below that desired for weldable steels. This steel had the second lowest order in the as-rolled condition and the lowest in the normalized condition.

431173—42——4

From most of the tests, steels which had been rolled at low temperatures in order to procure increased tensile strength generally had poor bending properties in the T-bend test. Many of these steels had considerably improved bending properties when the plates were normalized before welding.

Most excessively dirty or laminated steels did not have good bending properties. Such steels cannot be improved materially by normalizing, since nonmetallic inclusions cannot be eliminated or reduced by heat treatment.

VII. TESTS OF CAST AND WELDED FILLETS

A simple demonstration was made to show that the results of the T-bend test depended not on the size and shape of the specimen but on the effect of welding on the plate metal. Several cast-to-shape specimens were prepared from steels of different carbon contents; some were cast T-specimens with fillets; others were T-specimens without fillets, which later were welded in the same manner as the other T-specimens.

The specimens with and without fillets were poured adjacent to each other in the same mold and from the same molten metal, so that variables were a minimum. All specimens were normalized at 1,650° F before the fillets were welded. Specimens with cast fillets had bending properties superior to those of specimens with welded fillets. Examples of specimens of 0.10-percent-carbon steel are shown in figure 34. The specimen at the top with cast fillets had an angle of 66° at maximum load and bent to 120° without failure. The specimen at the bottom with welded fillets had an angle of 52° at maximum load and bent only to 63° before failure in the plate with a sharp report (type III fracture).

Similar tests made on specimens of 0.20-, 0.30-, 0.40-, and 0.50-percent-carbon steels gave similar results. Specimens with welded fillets, normalized after welding, had bending properties similar to those for specimens with cast fillets.

VIII. TESTS OF SPECIMENS OF VARIOUS WIDTHS

The nominal width of specimens was 1¼-in. To determine whether variations in this width would cause appreciable differences in bending properties, specimens of widths ranging from ½- to 1½-in. were machined from the same welded joints in ½-in. plates and tested.

Maximum loads were less for narrow specimens and higher for wider specimens than for those of nominal width. This was due primarily to the mass of metal in the joint, as previously discussed.

In the range from about ¾- to 1½-in., the angles of bending were not affected to any appreciable extent, all values falling within the usual scatter of the nominal size specimens. Specimens ¾-in. or less in width bent with slightly larger angles than normal, caused probably by edge effect. Specimens wider than 1½-in. could not be tested because of the limitations of the jig.

The type of fracture was the same regardless of width. It was not possible to change the type of fracture of the nominal width specimen from sharp (type III) to gradual (type II) or from plate (types II and III) to bond or weld (type I), or vice versa, by either increasing or decreasing the width of the specimen.

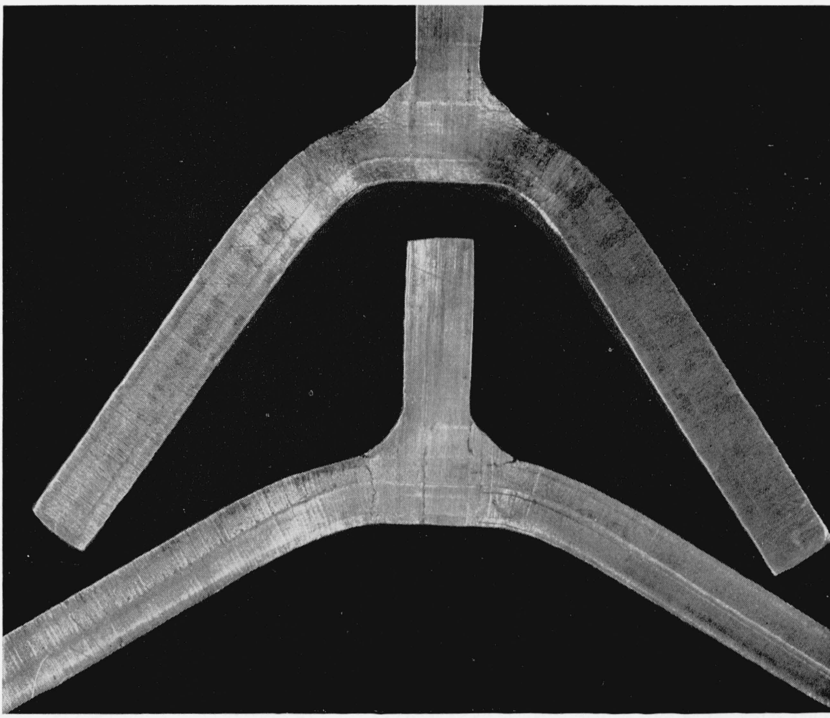

FIGURE 34.—*Cast and welded fillets tested in* T-*bend jig.*

The results of these tests indicate that minor departures from nominal widths, such as might be caused in the machining of specimens, had no appreciable effect on either the angle of bend or the type of fracture.

IX. SUMMARY

A method for testing the welding quality of steels has been described. Specimens of double fillet-welded T-sections were bent in a special bending jig.

Eighteen steels, generally in three thicknesses, ¼-, ½-, and ¾-in., and in two conditions, as-rolled and normalized, were tested. Some specimens were welded when the plates were at room temperature, others were made when the plates were at subnormal temperature as low as −20° F. Bend tests were made on these specimens at temperatures ranging from 70° to −20° F.

The angle of bend at maximum load and the type of fracture were the principal factors in determining welding quality.

A special method of analysis was used to evaluate the data.

No good correlation was found between any of the usual tensile properties or Vickers numbers of the steels and weldability; therefore they cannot be used for determining the welding quality.

Usually normalized plates had higher welding quality than the as-rolled plates of the same steels, due probably to relief of stresses set up during rolling and to a more homogeneous structure of the metal.

Most "dirty" steels had lower welding quality than clean steels.

Austenitic grain size and grain-coarsening temperatures apparently had little effect on welding quality.

Steels containing nickel and copper had the highest welding qualities of the steels tested, while those containing more than 0.70 percent of manganese had the lowest welding quality. Phosphorus greater than 0.10 percent also is believed to contribute to low welding quality in steels.

Plates welded at low temperatures had lower angles of bend and more plate metal failures than those welded at room temperature. The temperature of testing apparently had more effect on the angle of bend and plate metal failures than the temperature of the plates when welding was begun.

This bend test provides a reliable means for determining the welding quality of steels. A structural weld is tested without machining the surface, leaving the welds intact as deposited. The reproducibility of results of duplicate specimens is excellent. The angle of bending and the kind, extent, and location of the fractures are important criteria of the welding quality of steels and not a function of the shape of the specimen.

The views expressed in the foregoing paper are the personal opinions of the authors, and in no way express the opinions of the Navy Department and the National Bureau of Standards.

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