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Effect of Discontinuities on Weld Strength of Aluminum Alloys

Welds in low-strength and medium-strength alloys can tolerate more porosity than has been generally accepted and these welds can also tolerate more porosity than can welds in alloys of higher strength

BY F. G. NELSON AND MARSHALL HOLT

ABSTRACT. This paper presents results of radiographic examination and tensile tests on twenty-five examples of welded joints to document the effects of porosity and/or tungsten inclusions on the ultimate strength. It is indicated that welds in low-strength and medium-strength alloys can tolerate more porosity than has been generally accepted (rating of 1.5 on the Alcoa 7-film standard) and further they can tolerate more porosity than can welds in alloys of higher strength (3003 vs 6351, for example).

This paper presents a series of reproductions of radiographs of porosity and/or tungsten inclusions in weldments of various combinations of weldable aluminum alloys and the results of an evaluation of the effects of that porosity on the strength of the weldment.

Introduction

The porosity in a weldment is usually measured by visual comparison of a radiograph of that joint with radiographic standards representing various amounts of porosity. The sensitivity of a radiograph is judged on the basis of the shadow of a suitable penetrameter placed beside or on the weld bead during the exposure. Pores having diameters less than that of the smallest hole in the penetrameter are not easily detected. Penetrameters were used in making the radiographs of these example weldments but, in many cases, the images of the penetrameters do not show on the positive prints of the radiographs because of the loss of detail in the prints or the location on the panel from which the examples were cut.

For the purpose of this paper, tungsten inclusions will be considered as representing solid pores. Although, tungsten inclusions do not generally occur in weldments made with today's improved welding techniques, they may result if improper welding techniques are used.

Radiographs of specimens or portions of the panel from which the specimens were cut are presented, together with the results of tests performed on the particular specimens. In most cases, ratings of the welds were based on the Alcoa 7-film standard (Fig. 1). These ratings compare favorably with those based on the standards for welds illustrated in Section VIII of the ASME Boiler and Pressure Vessel Code. For some structural applications, ratings up to $1^1/_2$ have been considered as indicating satisfactory welds for thicknesses up to 2 or 3 in. However, it is recognized that the Alcoa 7-film standard has not been correlated with thickness. The question under consideration involves determination of an acceptable degree of porosity. The tensile strength of a weld is generally compared with a procedure qualification value, which for non-heat treatable alloys is usually the specified strength of annealed material and for heat treatable alloys, a statistically derived minimum based on tensile test results. Excessive porosity is considered to be that which leads to a strength below the qualification value provided of course that the welding technique was proper. This approach is implied by the comparisons in this paper with ASME qualification values.

Questions can be raised concerning the appropriateness of the use of radiographs for the evaluation of the soundness of a welded joint but no attempt will be made to answer those

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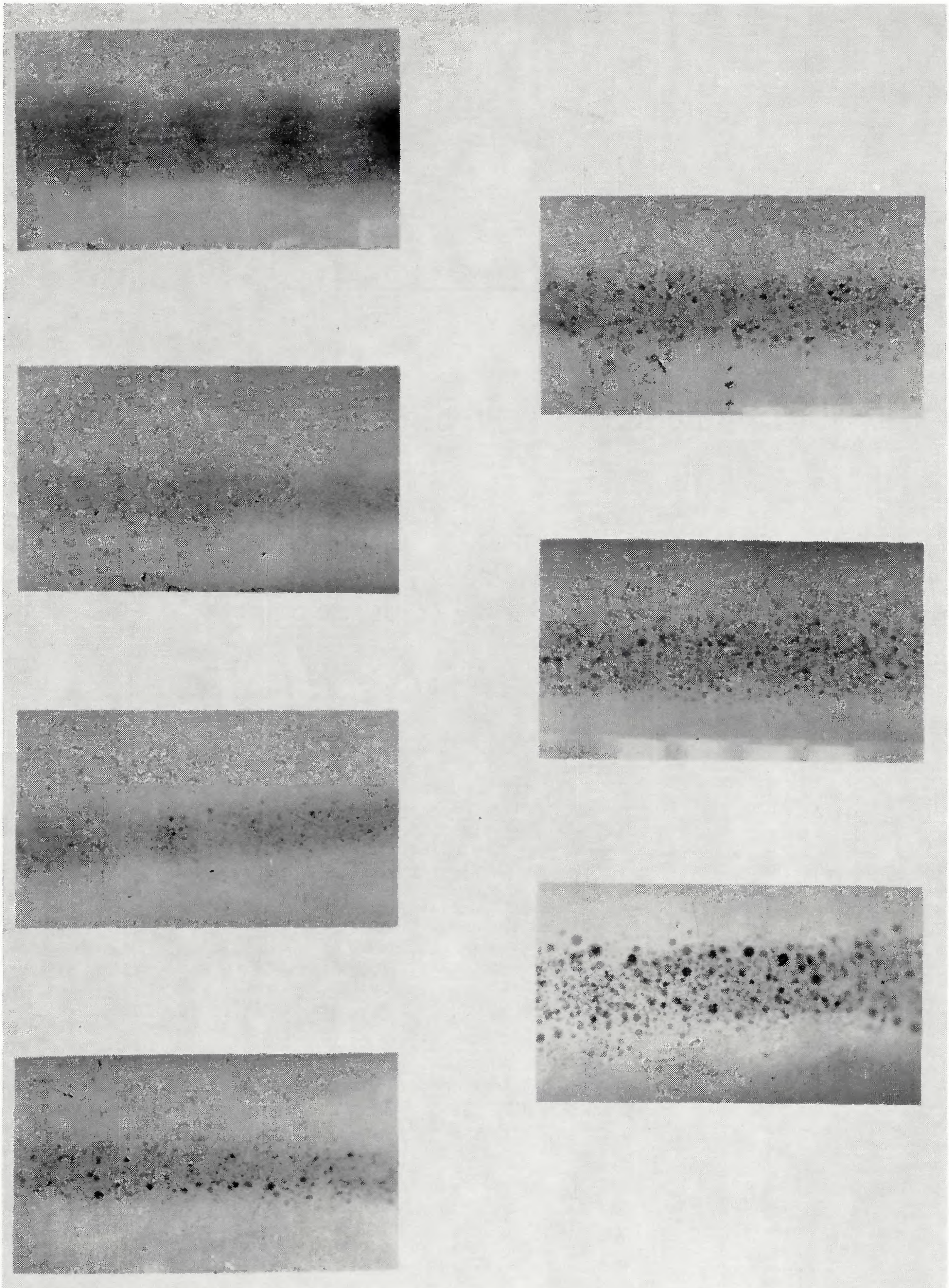

Fig. 1—Radiographic soundness ratings (Alcoa 7-film standard)

in this paper. Since the metallurgical structure of a deposited weld is similar to that of a sound casting, it is to be expected that all welds may contain microporosity and that the best way of determining the amount of microporosity is by counting the pores on the fracture surface and estimating their total cross-sectional area. However, if examination of the fracture surfaces is considered to be the best way to determine the extent of porosity in a joint, how does one make an examination of welds in production items which cannot be destroyed, for example, in a pressure vessel. Since such production items cannot be cut or pulled apart, radiography appears to be the best technique at present for examination of welds, including determination of porosity.

Parent and Filler Metals

This paper presents positive prints of radiographic images of welds as representative of the combinations of parent and filler metals as shown in Table 1 at end of article.

Description of Specimens

Generally, the types of specimens for which tensile or bend data are given in this report are shown in Fig. 2. The reduced-section tensile specimen is usually required by various codes (ASME, AWS, API) for the determination of the strength values for qualification of procedures. This specimen is designed to force fracture through the weld, thus revealing the extent of porosity and effects of other strength modifying factors in the weld. The full-section tensile specimen is similar to one shown in ASTM Method E8 and is a standard Alcoa specimen used for the determination of the joint yield strength. The specimen is designed to allow measurement of strain over a long gage length (10 in.) and fracture of the specimen at the weakest section in the long uniformly reduced test section.

Although 25 examples were investigated, for the purpose of this paper only six representative examples, good or bad, are discussed in detail: one each of a low strength and high strength non-heat treatable alloy, three examples of high strength heat treatable alloys and one example of a casting alloy.

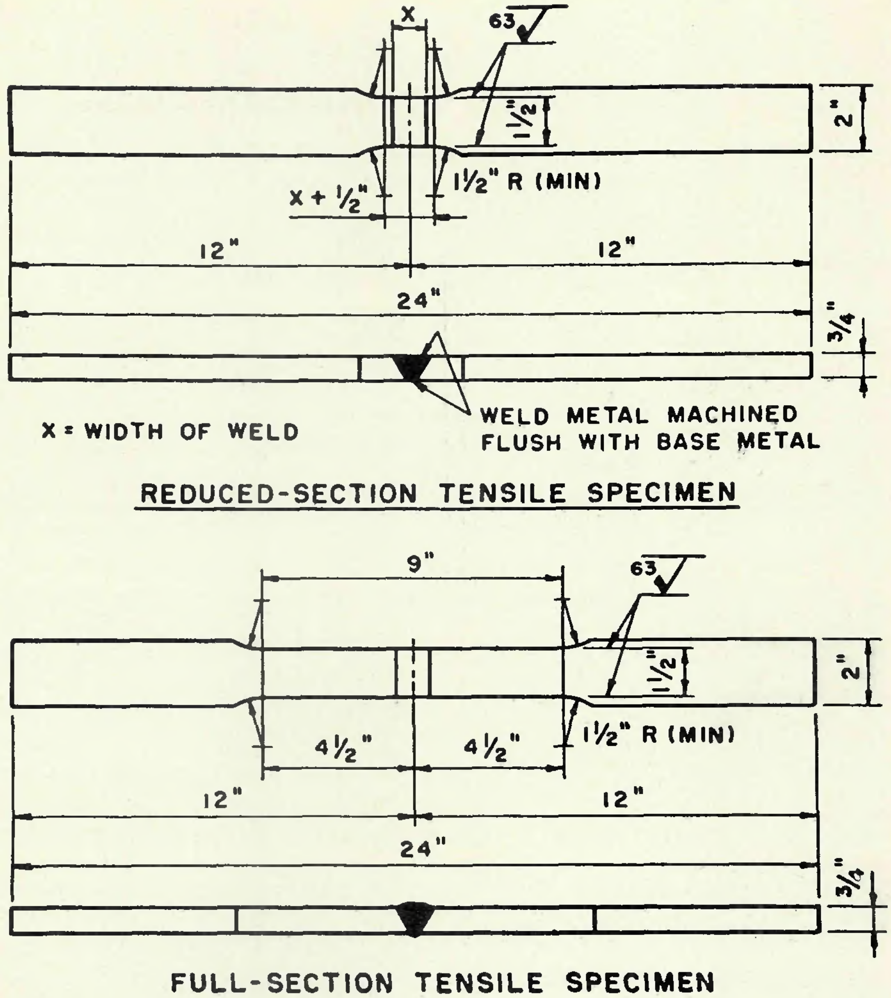

Fig. 2—Specimens from groove-welded plate

Wrought Alloys

Non-Heat Treatable Alloys. Figure 3 shows portions of a 1100 weld in a $^1/_2$-in. thick 3003-F panel welded with the gas tungsten-arc method (TIG); the radiographic rating of the tensile specimens (both reduced-section and full-section) ranged from 3 to 6 on the basis of Alcoa's 7-film standard shown previously. The ASME qualification requirement for the tensile strength of this panel is 14,000 psi; the tensile strengths of the specimens are from 8 to 12% above the qualification requirement. Thus, even though these specimens contained very large amounts of tungsten inclusion, the strengths are well above the qualification value based on the specified tensile strength of annealed plate. Based on this example, it is indicated that welds in 3003 plate can tolerate a very large amount of porosity.

The radiographic ratings of 5556 welds in a series of $^3/_8$-in. thick 5456-0 panels welded with a gas metal-arc method (MIG) ranged from 1.1 to 6.6; the corresponding strengths of reduced-section tensile specimens are shown in Table 1. The radiographic ratings of these panels were also based on the Alcoa 7-film standard. The ASME qualification value for panels of this parent material is 42,-000 psi. A plot of these data (Fig. 4) indicates that although the strength values decrease with increasing radiographic rating, the strength does not fall to the qualification value (42,000 psi) until the rating is about 3.0 to 3.5. The specimen with a rating of 3.5 might be considered unsatisfactory from the rating point of view (limiting rating = 1.5) but the tensile strength is 42,000 psi or equal to the qualification requirement.

Heat Treatable Alloys. Figure 5 shows the radiograph of a portion of a 4043 weld in a $^1/_2$-in. thick 6061 panel welded with the gas metal-arc method; the radiographic rating of the panel is about 2 on the basis of Alcoa's 7-film standard. The ASME qualification value for this parent metal in the as-welded condition is 24,000 psi. The tensile test values average about 22% above this qualification value. Even though the weld, as shown in Fig. 5, contained many large pores and thus had a radiographic rating greater than that considered acceptable, this panel met the strength requirement. It is highly improbable that the tensile test specimens did not contain some of the "large pores."

The second example concerns a weldment in 6061, a $^7/_8$-in. thick panel with the radiographic ratings in various portions ranging from $2^1/_2$ to 4 (Fig. 6). The tensile strengths of the

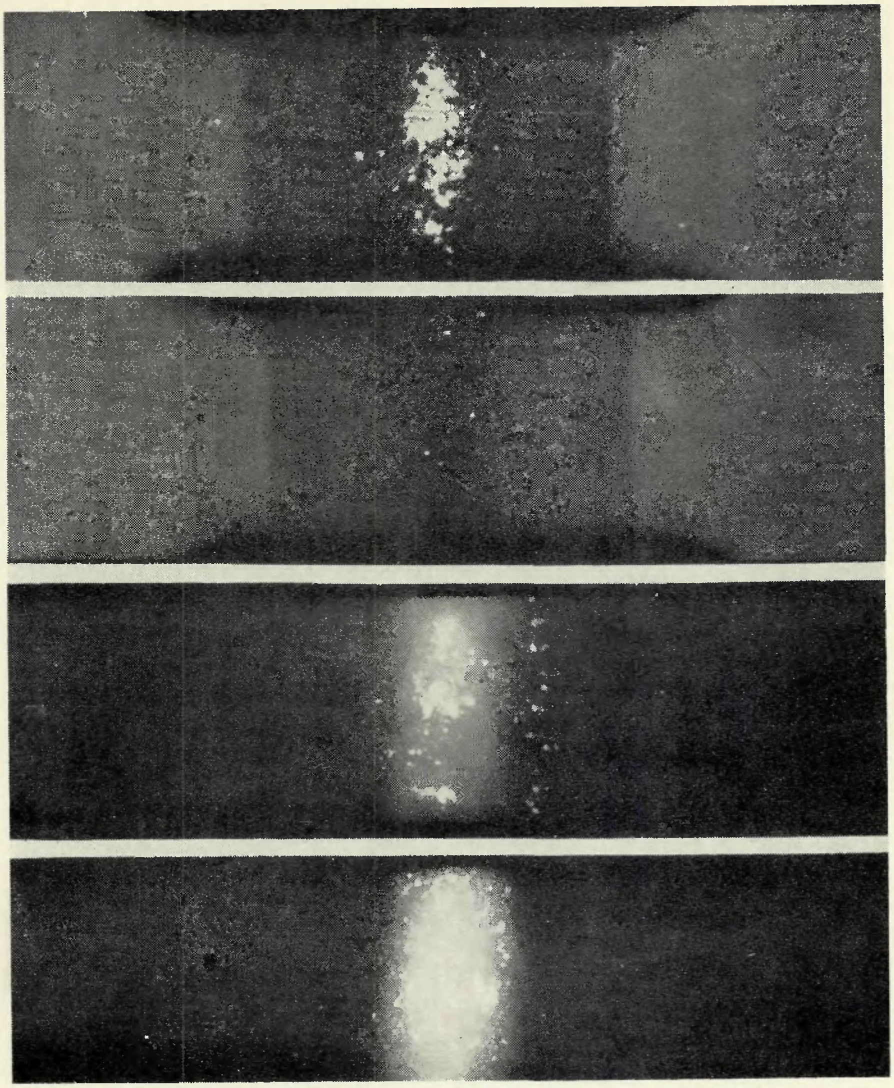

Fig. 3—Radiographic image of a 1100 weld in a ½-in. thick 3003-F panel welded with the gas tungsten-arc method

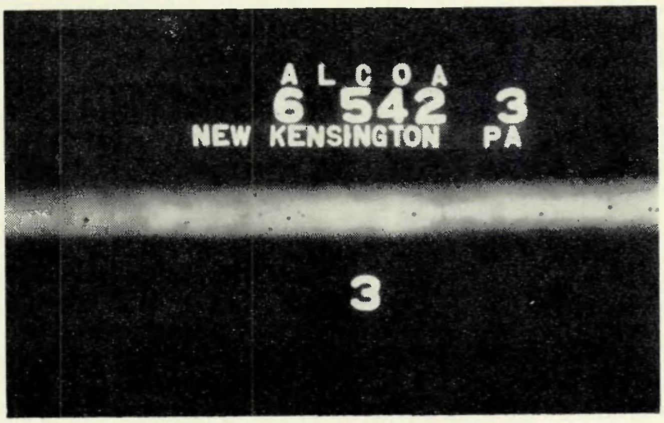

Fig. 5—Radiographic image of a 4043 weld in a ½-in. thick 6061-T651 panel welded with the gas metal-arc method

reduced-section specimens with ratings of 3 or 4 were about 21,000 psi and thus failed to meet the qualification requirement of 24,000 psi. In these cases, the fractures occurred through the weld, as might be expected with this specimen design. However, the full-section specimens fractured at the edge of or away from the weld and developed strengths above the qualification value.

The fracture surfaces of 5356 welds in 0.094-in. thick 6005-T5 and 6351-T5E37 panels welded with the

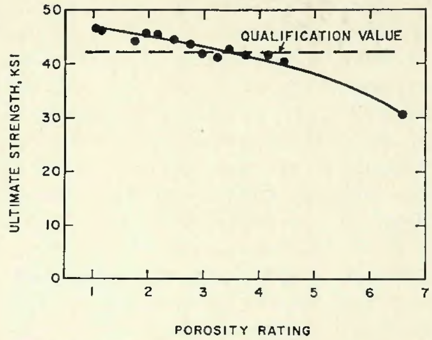

Fig. 4—Effect of porosity on the ultimate strength of 5556 welds in 5456-O plate (thickness=⅜ in.)

gas tungsten-arc method are shown in Fig. 7. The radiographic ratings range from 1.1 to 7.0. The tensile strengths are compared with the qualification requirement for 6061 since no code writing body has established values for these two alloys. As shown in Table I and Fig. 8, welds in these relatively thin panels of 6005 and 6351 would not consistently meet a qualification value of 24,000 psi if the radiographic rating is 2 or greater.

Casting Alloy

Non-Heat Treatable. As shown in the example of a 5556 weld in ½-in. thick 218-F cast plate welded with the gas metal-arc method, (Fig. 9) the radiographic ratings of the reduced-section tensile specimens ranged from 2 to 4 on the basis of Alcoa's 7-film standard. In the absence of a qualification value, the test values were compared with an average strength of 37,800 psi of sound porosity-free specimens. The data (Fig. 10) indicate that specimens with porosity ratings greater than 2 might develop strengths less than that developed by sound porosity-free specimens.

Summary

Based on the evaluation of 25 combinations of parent and filler metals with various radiographic ratings, six were discussed herein in detail. The non-heat treatable alloys are tolerant to a relatively high degree of porosity before the ultimate strength across the weld is decreased to a value below the qualification value. The tolerance to porosity of a higher strength non-heat treatable alloy is less than that of the lower strength non-heat treatable alloys as indicated by the results shown for welds in 5456. The degree of tolerance to porosity appears to be less for heat treatable and casting alloys. The supporting data of this paper are too meager to pinpoint the tolerance limit beyond which the strength of the weld joint will decrease below the qualification value; howev-

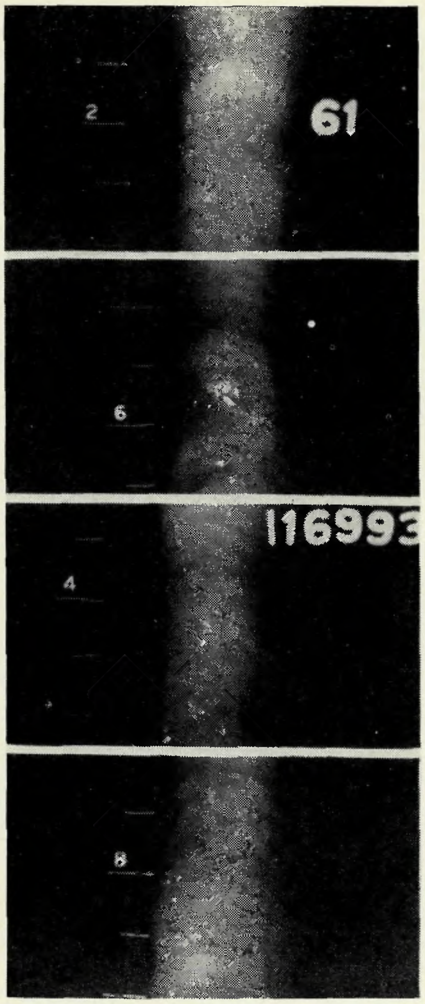

Fig. 6—Radiographic image of a 4043 weld in a ⅞-in. thick 6061-T651 panel welded with the gas tungsten-arc method

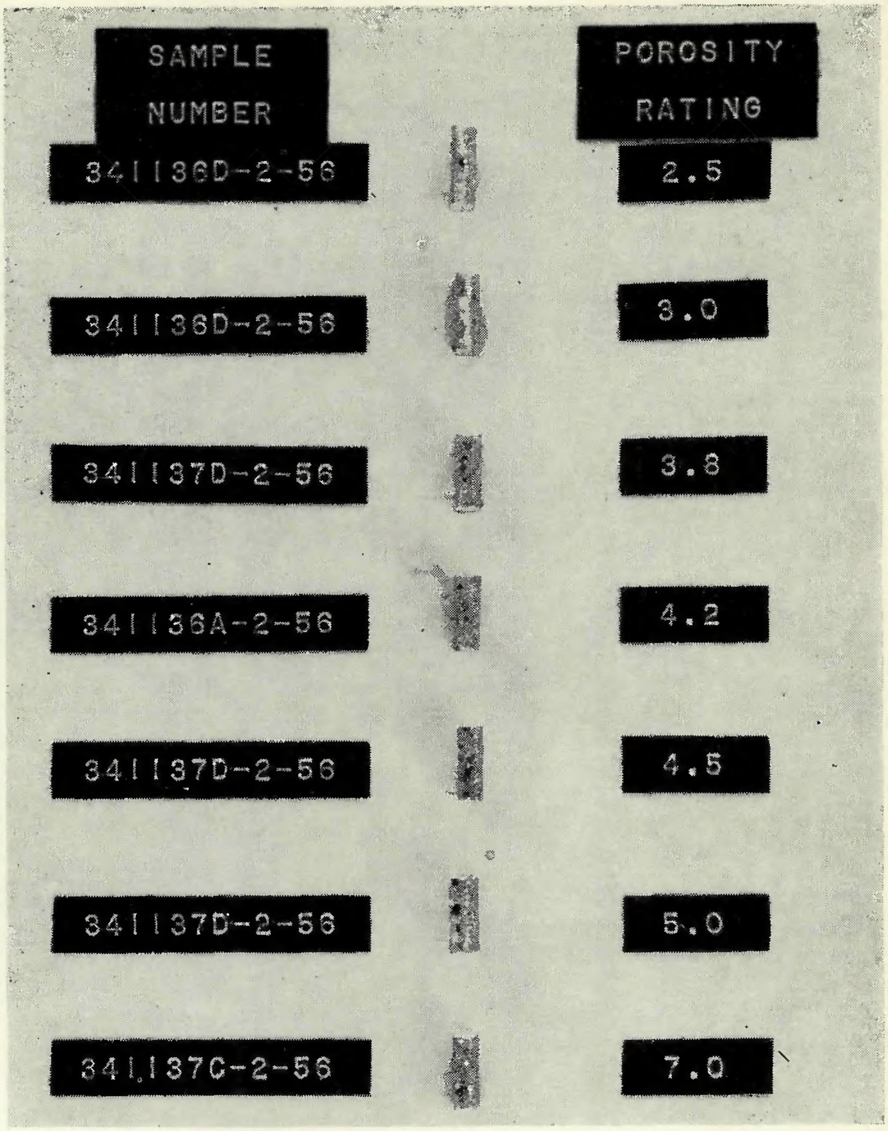

Fig. 7—Porosity ratings of groove welds in some 6005-T5 and 6351-T5E37 extrusions; 5356 filler metal/gas tungsten-arc method

er, they suggest that the tolerance limit is related to the tensile strength of the parent metal and the toughness of the weld as previously determined.

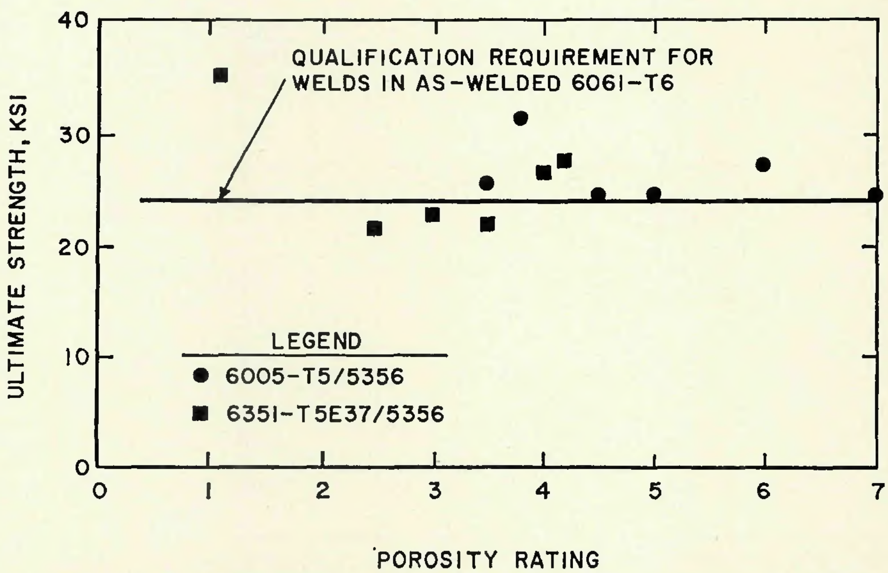

Fig. 8—Effect of porosity on the ultimate strength of 5556 welds in 6XXX extrusions (thickness=0.094 in.)

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Table 1—Radiographic Ratings and Quality as Indicated by Tensile Properties

Example number	Alloy and temper	Typical tensile strength, psi	Thick-ness, in.	Filler metal	Welding method[a]	Qualifica-tion require-ment,[b] psi	Radio-graphic[c] rating	Joint tensile strength, psi: Reduced-section specime	Joint tensile strength, psi: Full-section specime
1	1100-O	13,000	$\frac{3}{4}$	1100	TIG	11,000	4	12,900	—
			$1\frac{1}{16}$	1100	TIG	11,000	4	13,500	—
2	1100-F	13,000	$\frac{3}{4}$	1100	TIG	11,000	7	12,800	—
			$1\frac{1}{16}$	1100	TIG	11,000	7	13,500	—
3	1100-H14	18,000	$\frac{3}{4}$	1100	TIG	11,000	2	12,800	—
			$1\frac{1}{16}$	1100	TIG	11,000	7	12,800	—
4	3003-O	16,000	$\frac{3}{8}$	1100	TIG	14,000	3	15,800	15,400
			$\frac{3}{4}$	1100	TIG	14,000	7	16,400	—
			$1\frac{1}{16}$	1100	TIG	14,000	2	15,200	—
5	3003-O	16,000	$\frac{3}{8}$	1100	O-H	14,000	4	17,400	15,700
6	3003-F	16,000	$\frac{1}{4}$	1100	MIG	14,000	7	16,900	—
								17,000	—
7 (Fig. 3)	3003-F	16,000	$\frac{1}{2}$	1100	TIG	14,000	3 to 6	15,600	15,300
								15,500	15,200
8	3003-F	16,000	$\frac{3}{4}$	1100	TIG	14,000	2	16,300	—
9	3003-F	16,000	1	1100	TIG	14,000	1 to 7	17,000	—
10	3003-H14	22,000	$\frac{1}{4}$	1100	TIG	14,000	7	16,200	—
11	3004-F	26,000	1	3004	MIG	22,000	5	—	24,300
1	5052-H32	33,000	$\frac{5}{8}$	5052	TIG	25,000	4 to 7	24,600	27,600
								25,500	22,500
13	5052-H32	33,000	$\frac{7}{8}$	5052	TIG	25,000	$2\frac{1}{2}$ to 7	23,900	29,000
								24,700	29,400
14 (Fig. 4)	5456-O	45,000	$\frac{3}{8}$	5556	MIG	42,000	1.1	46,600	
							1.2	46,400	
							1,8	44,200	
							2.0	45,500	
							2.2	45,400	
							2.5	44,500	
							2.8	43,700	
							3.0	42,000	
							3.3	41,400	
							3.5	42,600	
							3.8	41,800	
							4.0	39,200	
							4.2	41,600	
							4.5	40,500	
							6.6	30,500	
15 (Fig. 7)	6005-T5		0.094	5356	TIG	24,000[d]	3.5		25,600
							3.8		31,500
							4.5		24,600
							5.0		24,500
							6.0		27,200
							7.0		24,700
16 (Fig. 5)	6061-T6	45,000	$\frac{1}{2}$	4043	MIG	24,000	2	28,600	29,500
17 (Fig. 6)	6061-T6	45,000	$\frac{7}{8}$	4043	TIG	24,000	$2\frac{1}{2}$ to 4	20,200	24,800
								21,400	25,500
18	6061-T6	45,000	1	4043	TIG	24,000	7	21,200	—
19	6061-T6	45,000	1	4043	TIG	24,000	3 to 7	24,100	—
20	6061-T6	45,000	1	4043	TIG	24,000	3 to 4	18,800	25,400
								21,400	21,800
21 (Fig. 7)	6351 T5E37	—	0.094	5356	TIG	24,000[d]	1.1		35,200
							2.5		21,200
							3.0		22,800
							3.5		21,900
							4.0		26,600
							4.2		27,600
22	6351-T6	—	$\frac{1}{4}$	4043	TIG	24,000[d]	2 to 3	30,900	36,000
								31,500	37,000
								33,000	35,800
								31,600	34,000
23 (Fig. 9)	218-F	—	$\frac{1}{2}$	5556	MIG	37,800[e]	2 to 4	33,400	—
								31,400	—
								33,700	—
24	A344-F	—	$\frac{1}{2}$	4043	MIG	24,300[e]	2	24,200	—
								24,500	—
25	A344-F 6061-T6	—	$\frac{1}{2}$	4043	MIG	24,600[e]	3	24,800	—
								24,800	—

[a] TIG = gas tungsten-arc; MIG = gas metal-arc.
[b] Based on Section IX of ASME Boiler and Pressure Vessel Code, except as noted.
[c] Rating of panel or specimen based on Alcoa 7-film standard.
[d] Value for welds in 6061-T6; qualifcation vaues for welds in this parent metal not established.
[e] Average value based on tests of sound porosity-free specimens.

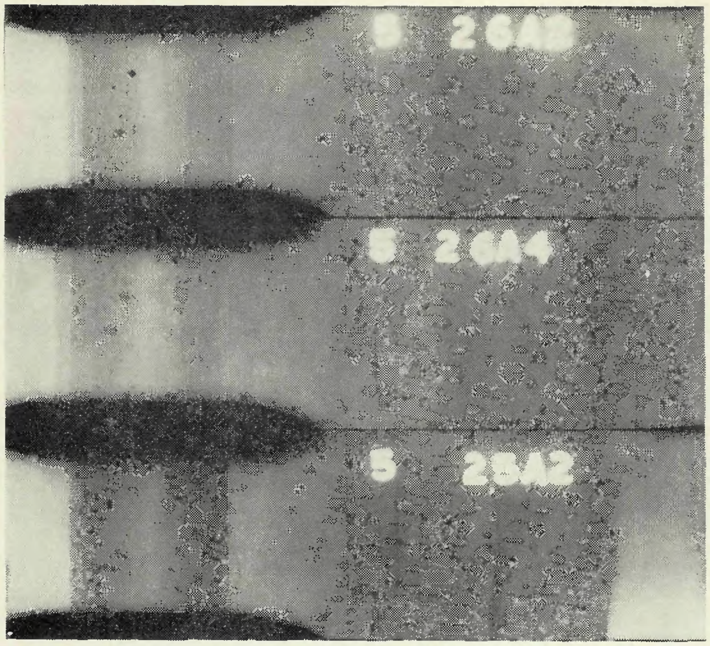

Fig. 9—Radiographic image of a 5556 weld in a ½-in. thick cast 218-F panel welded with the gas metal-arc method

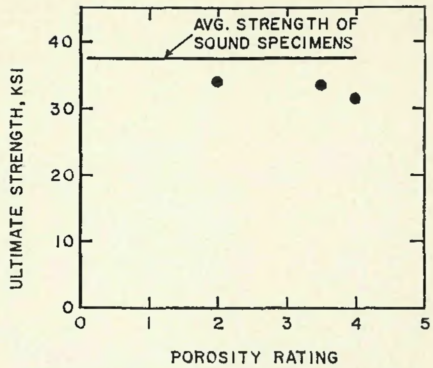

Fig. 10—Effect of porosity on the ultimate strength of 5556 welds in 218-F casting alloy (thickness=½ in.)

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