Fatigue of Aluminum Alloy Welded Joints

The results of axial-stress and repeated-bending loading tests on welded thin-gage alloys indicate joint geometry has the greatest effect on fatigue strength

BY N. L. PERSON

ABSTRACT. A study of aluminum alloy butt, lap and tee welded joints under axial-stress loading and of butt welds under repeated-bending loading (all of thin-gage plate materials) revealed that their fatigue strengths were affected foremost by the geometric characteristics of the joints. The degree of stress concentration and of symmetry with respect to the load axis both contribute to the following order of decreasing axial-stress fatigue strength for the joints investigated:

1. Butt, bead on.
2. Butt, bead off.
3. Tee, double fillet.
4. Lap, double fillet.
5. Lap, single fillet.
6. Tee, single fillet.

Only small differences were found between the last three joints listed, all of which had substantially lower fatigue strengths than the three joints rated above them. The base metal and filler metal alloys apparently had less effect on fatigue strength than the geometric factors.

For any given type joint (butt, lap or tee), the weld size and shape were prime factors affecting their fatigue strengths (except bead-off butt welds). The highest fatigue strength for bead-on butt joints was obtained from welds with low-profile reinforcements and high tensile strength. Fillet welds with a convex shape produced lower fatigue strengths for both lap and tee joints. Tee joints with fillet welds substantially oversize and with the welds blending smoothly into base metals had the highest fatigue strength for that type joint.

Introduction

In the past couple of decades, a number of weldable high-strength aluminum alloys have been developed. Alloys that have received wide acceptance include 5083, 5086, 5456 and 7039. These alloys have been used for many applications, such as pressure vessels, ship superstructures, railroad cars, military vehicles and highway trailers.

N. L. PERSON is Senior Research Engineer, Kaiser Aluminum & Chemical Corp., Pleasanton, Calif.

The fatigue strength of an aluminum plate material with welds is generally lower than that of the base metal. Such factors as stress concentrations and variations in physical and mechanical properties in the weld area contribute to that difference. Although fatigue must be considered in the design of many structures, the literature contains little fatigue data for weldments in the newer alloys. This paper partially fills that void by presenting fatigue data for butt, lap and tee-welded joints. Several base and filler metals alloys were included in the study.

Materials

All base and filler metals used to prepare the welded joints were regular production materials. Table 1 gives the chemical compositions of the base and filler metals.

Generally, the weld joints were made with plate of nominal $^3/_8$ in. thickness. Alloys 5052 and 6061 were used in $^3/_{16}$ and $^1/_4$ in. thicknesses, respectively, because a specific application required data from material of those thicknesses. Table 2 lists the tensile properties of the unwelded plates.

Welding Procedures

The following three types of welded joints (Fig. 1) were evaluated:

1. Butt, weld bead-on and bead-off (axial-stress and repeated-bending fatigue tests).
2. Lap, single and double-fillet joints (axial-stress tests only).
3. Tee, single and double-fillet joints (axial-stress tests only).

All welding was done in the flat position using the gas metal-arc process. Table 3 gives specific details of welding conditions. Generally, the weldment measured 24 in. along the weld axis; except for the tee joints, which were 12 in. long. All welds were allowed to age at room temperature for at least 30 days before being tested.

Butt Joints

All the butt joints were of the single-vee-groove design (60 to 70 deg) with $^1/_{16}$ to $^1/_4$ in. lands, except for the $^3/_{16}$ in. 5052 sheet welds which were square-butt design. Only the butt joints for the repeated-bending tests had a root opening ($^1/_{16}$ in.). The butt joints for the repeated-bending tests were welded with two superimposed passes on the face side and one pass on the back side (total of three weld passes); the 7039-T61 (5039) joints were an exception in that these were welded with only one pass on each side. The 7039-T61 (5039) butt joints were prepared with very low weld-bead profiles (bead height about 13% of base metal thickness). One face pass and one back pass were also used for the butt joints for axial-stress testing. The root pass was back chipped before the back pass, except for the $^3/_{16}$ in. 5052 welds. Alloy 5083-to-6161 dissimilar joints (both base metals were $^3/_8$ in. thick) were inluded.

The butt welds were radiographed to determine their soundness (welds in lap and tee joints were not radiographed). Only those butt welds with a porosity rating of 2 or better according to the porosity standards shown in Fig. 2 were tested. The maximum amount of porosity (in size and number) permitted by the ASME Boiler and Pressure Vessel Code corresponds approximately to rating no. 5 and 6 in Fig. 2.

Lap Joints

As shown in Fig. 1, lap joints were prepared with one or two fillet welds. Each fillet was made in one pass. The overlap of the base plates was $1^1/_2$ in. for the single-fillet joint and 1 in.

Table 1—Chemical Composition of Test Materials

Material			Type of fatigue test performed	Element, wt-%							
Alloy	Temper	Thickness, in.		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
5052	-H32	3/16	Axial stress	0.11	0.28	0.05	0.04	2.49	0.20	0.07	0.02
5083	-H113	3/8	Axial stress	0.14	0.28	0.07	0.70	4.42	0.10	0.05	0.02
			Repeated bending	0.09	0.20	0.03	0.65	4.45	0.12	0.03	0.02
	-H321	3/8	Axial stress	0.14	0.24	0.08	0.67	4.40	0.11	0.04	0.02
5086	-H32	3/8	Axial stress	0.10	0.25	0.05	0.50	4.08	0.13	0.17	0.03
5456	-H321	3/8	Repeated bending	0.08	0.23	0.07	0.68	5.38	0.10	0.04	0.01
6061	-T6	1/4	Axial stress	0.73	0.52	0.23	0.07	0.99	0.25	0.06	0.01
		3/8	Axial stress	0.64	0.44	0.23	0.05	0.95	0.23	0.07	0.02
7039	-T61	3/8	Axial stress and repeated bending	0.08	0.21	0.05	0.28	2.51	0.17	3.74	0.03
	-T6 type experimental temper	3/8	Repeated bending	0.06	0.16	Trace	0.22	2.83	0.18	3.85	0.02
Filler metal	Type joint										
5039	Butt and lap		Axial stress	0.03	0.20	0.02	0.46	3.41	0.12	2.53	0.02
	Tee		Axial stress	0.07	0.25	0.005	0.47	3.83	0.13	2.55	0.02
	Butt		Repeated bending	0.08	0.17	0.06	0.37	3.63	0.11	3.38	0.02
5183	Butt		Axial stress	0.06	0.20	0.01	0.60	5.13	0.07	0.02	0.02
	Butt		Repeated bending	0.09	0.16	Trace	0.64	4.63	0.14	0.02	0.05
5356	Butt		Axial stress	0.05	0.11	0.01	0.11	5.06	0.09	0.03	0.08
	Lap		Axial stress	0.04	0.12	0.02	0.10	4.94	0.08	0.03	0.07
	Tee		Axial stress	0.10	0.12	0.06	0.12	4.85	0.09	0.03	0.07
5556	Butt		Repeated bending	0.09	0.15	0.05	0.61	4.95	0.10	0.02	0.02

Table 2—Tensile Properties of Base Metals

				Longitudiual dir.			Tranvserse dir.		
Alloy	Temper	Thickness, in.	Type of fatigue test performed	Tensile strength, ksi	Yield strength, ksi	Elongation in 1.4 in., %	Tensile strength, ksi	Yield strength, ksi	Elongation in 1.4 in., %
5052	-H32	3/16	Axial stress	34.3	26.0	15.2	34.9	24.9	15.7
5083	-H113	3/8	Axial stress	51.9	39.0	14.1	51.4	34.2	19.0
			Repeated bending	48.8	38.0	16.1[a]	47.9	32.4	20.6[a]
	-H321	3/8	Axial stress	49.1	30.5	20.7	49.5	27.5	22.6
5086	-H32	3/8	Axial stress	47.4	37.3	17.1	47.2	33.1	18.4
5456	-H321	3/8	Repeated bending	53.3	36.2	17.0[b]	52.1	34.4	18.0[b]
6061	-T6	1/4	Axial stress	45.8	43.2	15.5	46.0	40.8	14.3
	-T6	3/8	Axial stress	44.6	40.4	12.9	44.2	38.3	12.1
7039	-T61	3/8	Axial stress:						
			Butt joints	58.3	48.2	19.1	58.3	47.9	18.4
			Lap and tee joints	58.3	50.1	17.1	58.5	49.0	15.9
			Repeated bending	58.3	48.2	19.1	58.3	47.9	18.4
	-T6 type experimental temper	3/8	Repeated bending	65.9	59.3	15.2	67.3	58.6	14.2

[a] Elongation in 2 in.
[b] Elongation in 1 in.

for the double-fillet joint.

Two types of dissimilar alloy joints were prepared. One was $^3/_{16}$ in. 5052 welded to $^1/_4$ in. 6061 and the other was $^1/_4$ in. 6061 to $^3/_8$ in. 5083 (for dissimilar joints, the thinner of the two base materials will be mentioned first).

Tee Joints

Single-fillet and double-fillet joints were welded (Fig. 1). Dissimilar-alloy joints were prepared with the same alloys used in making the lap joints. For the 5052-to-6061 joints, the thinner 5052 sheet was the load-carrying member (in subsequent tensile and fatigue tests), as shown in Fig. 1. In the 6061 to 5083 joints, the 6061 sheet was the load-carrying member.

Table 4 gives the results of tensile

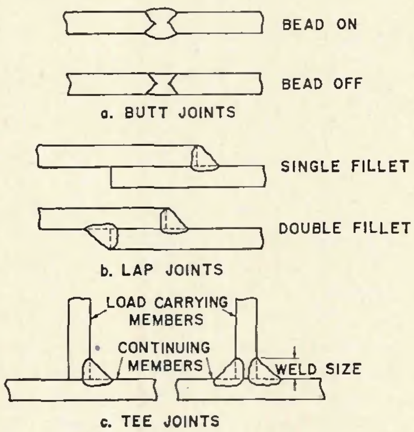

Fig. 1—Configuration of welded joints

tests conducted with $^1/_2$ in. wide specimens of each type joint. Only the tensile strength is reported for the lap and tee joints. For the dissimilar-alloy lap joints, the tensile strength was based on the cross-sectional area in the thinner of the two base metals.

As expected, the butt welds with the weld reinforcement (bead-on) had higher tensile strengths than the bead-off welds. Also the double-fillet lap and tee joints had substantially higher tensile strengths than the corresponding single-fillet joints. For the single-fillet lap joints the highest tensile strengths were obtained when the two base metals had unequal thicknesses and the fillet weld was on the edge of the thinner of the two plates.

Table 3—Typical Welding Conditions[e]

Base metal		Filler metal				
Alloy(s)	Thickness, in.	Alloy	Diameter, in.	Amperes	Arc volts	Travel, ipm
Butt joints:						
5052-H32	3/16	5356	0.045	190	23	42
5083-H113	3/8	5183	1/16	230	25	15
5083-H113	3/8	5356	3/32	300, 250[a]	25, 24[a]	16, 24[a]
5083-H113 to 6061-T6	3/8	5356	3/32	300	25	17
5086-H32	3/8	5356	1/16	295, 270[b]	23	14
5456-H321	3/8	5556	1/16	250	25	18
7039-T61	3/8	5183	1/16	250	23	22
7039-T61	3/8	5039	1/16	235, 225[b]	25, 26[b]	23, 17[b]
7039-T6	3/8	5039	3/32	300	23	18
Lap joints:						
5052-H32	3/16	5356	0.045	200, 180[b]	24	34
5052-H32	3/16					
to 6061-T6	1/4	5356	0.045	180	22	24
5083-H113	3/8	5356	3/32	270	24	24
5083-H113	3/8					
to 6061-T6	1/4	5356	1/16	270, 260[c]	25, 22[c]	34, 16[c]
7039-T61	3/8	5039	1/16	230	24	18
Tee joints:						
5052-H32	3/16	5356	3/64	170	20	20
5052-H32	3/16					
to 6061-T6	1/4	5356	3/64	170	20	20
5083-H113	3/8	5356	3/32	270	24	24
5083-H321[d]	3/8	5356	3/32	325	24	12
5083-H113	3/8					
to 6061-T6	1/4	5356	1/16	235	22	20
7039-T61	3/8	5039	1/16	275	24	14

[a] First value is for bead-on specimens and second one is for bead-off specimens.
[b] When two values listed, first value is for first weld pass or fillet.
[c] First value is for weld on edge of 6061 plate and second one is for weld against 5083 plate.
[d] Fillet welds made substantially larger than base metal thickness.
[e] Gas metal-arc process used exclusively; interpass temperature was room temperature for all welds.

Test Procedures

The axial-stress and repeated-bending test specimens are shown in Fig. 3. Bead-off butt weld specimens were prepared by machining off the weld reinforcements and about 0.005 in. from the surface of the base metal. The machining marks ran parallel to the length of the specimen. Prior to start of the fatigue tests, the sharp corners of the specimen tests sections were rounded slightly with $^3/_0$ emery paper.

Two MTS Systems Corporation electrohydraulic test systems (10 and 50 kip capacities) were used for the axial-stress tests. The butt and lap-joint specimens were loaded axially using pin-type grips. Figure 4 shows how the tee-joint specimens were loaded in these test machines. The test frequencies ranged from about 2 to 60 Hz. Krouse plate-bending fatigue machines were used for the repeated-

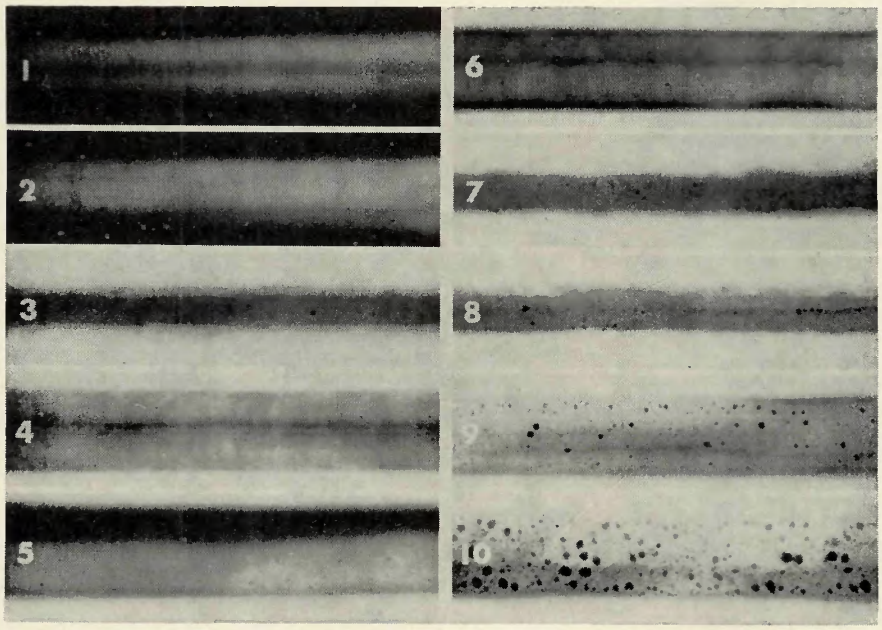

Fig. 2—Radiographic porosity standards for aluminum welds developed and used in the welding laboratories of Kaiser Aluminum & Chemical Corp.

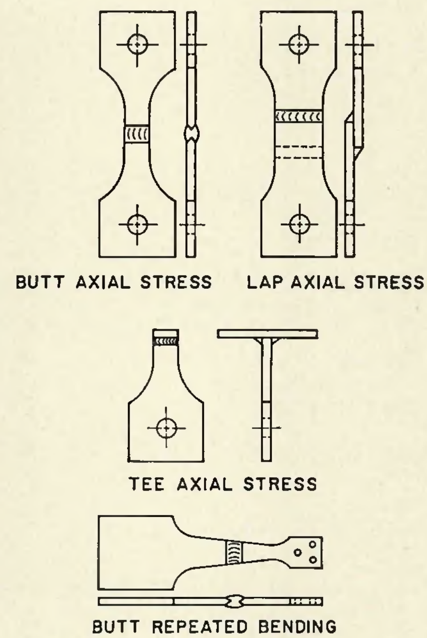

Fig. 3—Fatigue test specimens

bending test. Their testing speed was 1725 cpm.

Generally, the axial-stress tests were conducted at a stress ratio

$$\left(R = \frac{\text{Minimum Stress}}{\text{Maximum Stress}}\right)$$

approximately equal to zero. The minimum stress was kept slightly above zero to prevent backlash in the grips at the minimum stress. Also, limited tests were conducted on 5083-to-6061 butt joints with $R = 0.5$. The axial-stresses reported are equal to the axial loads (1b) divided by the cross-sectional area of the base plate (sq. in.) immediately adjacent to the weld.

In the case of the bead-off butt joints, the area was measured at the weld. The thickness of the base metal adjacent to the weld was used to establish the bending stress in the repeated-bending specimen. The tests were usually continued to failure, or they were stopped if they exceeded 10 million cycles in the axial-stress tests and 100 million cycles in the repeated-bending tests. Exceptions exist for specimens which broke at the grip and which, therefore, were considered as not having failed. They are plotted in the S-N diagrams at the point where they failed at the grip.

Results and Discussion

Butt Welds in Axial Stress

Figures 5 and 6 show the range of fatigue data expected of welded butt joints in the bead-on and bead-off conditions, respectively. Alloy 7039 butt welds welded with 5039 filler metal had the highest fatigue strengths in both the head-on and bead-off conditions (Table 5). One of the reasons for the high bead-on and bead-off fatigue strength for 7039 (5939) welds was that the weld reinforce-

Table 4—Tensile Properties of Welded Joints (Transverse to Weld Axis)

Material: Alloy[a]	Material: Thickness, in.	Weld condition	Tensile strength, ksi	Yield strength, ksi	Elongation in 1.4 in., %
Butt joints:					
5052–H32 (5356)	3/16	Bead on	32.0	20.3	12.2
		Bead off	29.8	17.8	10.4
5083–H113 (5183)	3/8				
Axial-stress tests		Bead on	47.0	21.8	12.6
		Bead off	42.7	20.6	13.7
Repeated-bending tests		Bead on	48.1	27.0	16.5[b]
		Bead off	44.5	25.1	15.2[b]
5083–H113 (5356)	3/8	Bead on	46.9	22.9	11.2
		Bead off	42.1	21.8	12.5
5083–H113 to 6061–T6 (5356)	3/8	Bead on	29.8	19.1	8.4
		Bead off	(No data)		
5086–H32 (5356)	3/8	Bead on	44.9	22.1	15.8
		Bead off	40.0	20.4	15.1
5456–H321 (5556)	3/8	Bead on	50.2	25.2	14.0[b]
		Bead off	44.6	21.4	13.0[b]
7039–T61 (5183)	3/8	Bead on	51.6	31.6	11.2
		Bead off	40.7	27.2	6.0
7039–T61 (5039)	3/8				
Axial-stress tests		Bead on	51.8	31.6	11.5
		Bead off	51.5	31.0	11.5
Repeated-bending tests		Bead on	52.8	35.4	11.2
(Low-profile beads)		Bead off	49.2	31.7	12.5
7039 (–T6 Type Temper, 5039)	3/8	Bead on	51.1	24.5	7.0[b]
Lap joints:					
5052–H32 (5356)	3/16	Single fillet	21.7		
		Double fillet	31.3		
5052–H32	3/16	Single fillet	23.5	Welded on edge of 5052 sheet	
to 6061–T6 (5356)	1/4	Single fillet	15.4	Welded on edge of 6061 plate	
		Double fillet	31.3		
5083–H113 (5356)	3/8	Single fillet	16.1		
		Double fillet	38.5		
6061–T6	1/4	Single fillet	23.0	Welded on edge of 6061 plate	
to 5083–H113 (5356)	3/8	Single fillet	18.9	Welded on edge of 5083 plate	
		Double fillet	34.9		
7039–T61 (5039)	3/8	Single fillet	18.4		
		Double fillet	42.2		
Tee joints:					
5052–H32 (5356)	3/16	Single fillet	16.0		
		Double fillet	32.1		
5052–H32	3/16	Single fillet	15.4		
to 6061–T6 (5356)[c]	1/4	Double fillet	32.6		
5083–H113 (5356)[d]	3/8	Single fillet	13.6		
		Double fillet	38.8		
5083–H321 (5356)[c]	3/8	Single fillet	21.2		
		Double fillet	49.8		
6061–T6	1/4	Single fillet	19.1		
to 5083–H321 (5356)	3/8	Double fillet	37.8		
7039–T61 (5039)	3/8	Single fillet	16.1		
		Double fillet	51.0		

[a] Alloy in parentheses is filler metal.
[b] Elongation in 2 in.
[c] Oversize fillet welds.
[d] Undersize fillet welds.

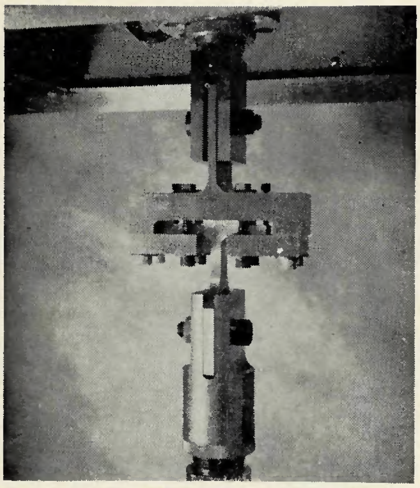

Fig. 4—Method of loading tee joints in axial stress

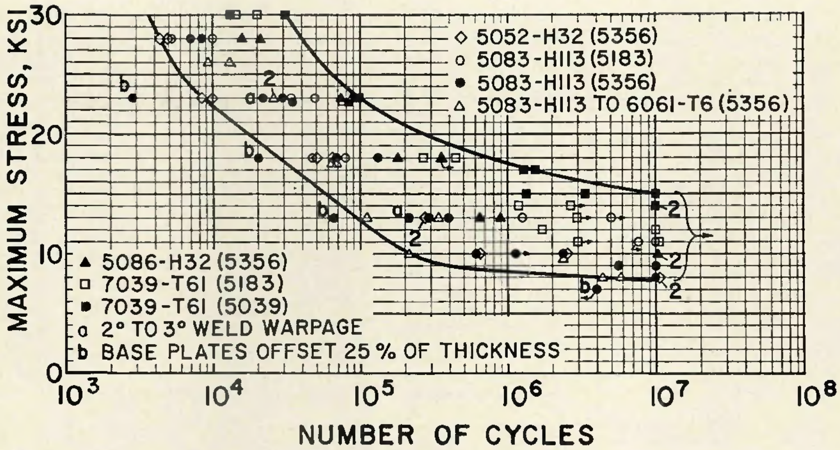

Fig. 5—Axial-stress fatigue data for bead-on butt joints, R=0

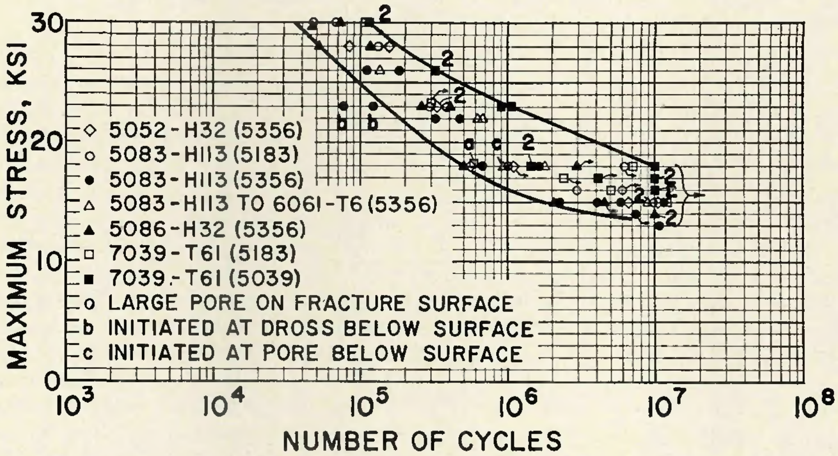

Fig. 6—Axial-stress fatigue data for bead-off butt joints, R=0

ments had a lower profile than welds in the other alloys. (On the other hand, the 7039 (5039) bead-on welds might have had an even higher tensile strength if the reinforcements had been larger.) The reinforcement profile influences the fatigue strength, because the stress concentration at the toe of the weld bead changes as the profile changes.

A number of investigators have studied relationships between fatigue strength of bead-on butt welds and the stress concentration at the toe of the weld reinforcement.[1-4, 6-8] Often they used photoelastic models to determine elastic stress concentration factors. [1, 2, 6] Probably one of the most comprehensive studies of that type was reported by Trufyakov et al.[6] That work used the following equation, which relates the stress concentration factor to the height and width of the weld bead and the radius of the weld toe:

$$K_t = l + \frac{2}{\pi A}\left[R \log \frac{l + r}{r} - R_0 + r_1 - r_1^2 R_2 + T_0\right]$$

where l is the width of the weld bead, r is the radius of the weld toe, and the other coefficients are dependent on ratios of the joint dimensions (not specifically defined by Trufyakov et al).[6] The equation was originally proposed by Navrotskii.[9]

Table 5—Axial-Stress Fatigue Strengths of Welded Butt Joints (Stressed Tranvserse to Weld Axis)

Material				Fatigue strength, ksi, at indicated number of cycles			
Alloy(s)	Thickness, in.	Filler metal	R^a	10^4	10^5	10^6	10^7
Bead-on:							
5052–H32	3/16	5356	0	22.5	15.5	10.5	8
5083-H113	3/8	5183	0	27	17	13.5	11
		5356	0	27	17.5	10.5	9
5083-H113 to 6061-T6	3/8	5356	0	26.5	16	9.5	7.5
			0.5	—	27.5	18.5	15.5
5086-H32	3/8	5356	0	30	22	12	10
7039-T61	3/8	5183	0	32	22	15.5	10.5
		5039	0	33	22.5	17.5	14
Bead-off:							
5052-H32	3/16	5356	0	—	28.5	17	15
5083-H113	3/8	5183	0	—	28.5	19	15
		5356	0	—	27.5	18	14
5083-H113 to 6061-T6	3/8	5356	0	—	27	20	15
			0.5	—	—	26.5	21
5086-H32	3/8	5356	0	—	27	18.5	14
7039-T61	3/8	5183	0	—	30	20	15
		5039	0	—	30.5	21.5	17

[a] $R = \frac{S_{min}}{S_{max}}$; S_{min} = 0.2 ksi for all tests; therefore, R values are approximate.

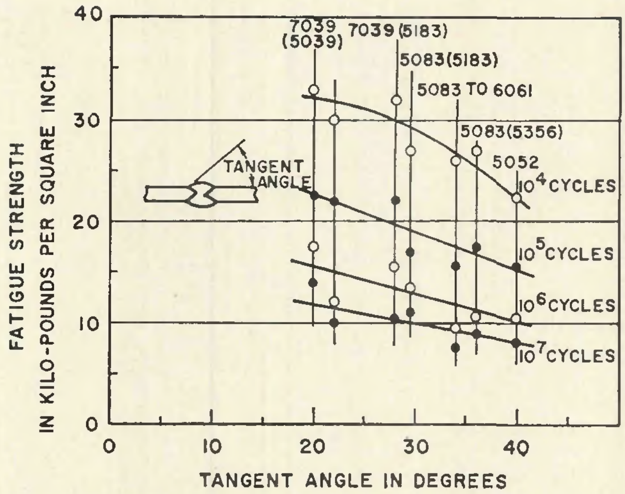

Fig. 7—Butt weld (bead on) fatigue strength vs. tangent angle at toe of weld bead (axial stress, R=0)

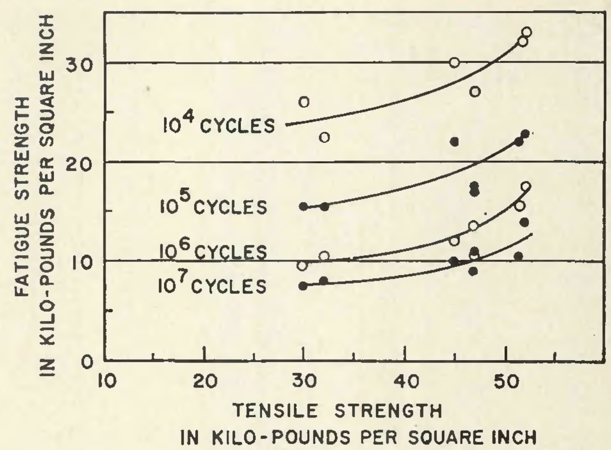

Fig. 8—Butt weld (bead on) fatigue strength vs. tensile strength (axial stress, R=0)

A simpler measure of the stress concentration due to the bead was used by other workers.[3, 4, 7, 8] The angle between the tangent to the weld bead and the plate surface was measured at the toe of the bead.

A general trend of increasing fatigue strength with decreasing tangent angle was observed for aluminum alloy and steel weldments. Figure 7 shows the results of a similar analysis for the welds in this study. The angles were measured from photographs of cross sections of the welds. The curves indicate a trend similar to that found in the earlier work—that of increasing fatigue strength with decreasing tangent angle. The effect is more prominent for 10^4 and 10^5 stress cycles than at the longer fatigue lives. Since the bead size is primarily affected by the arc travel speed, the bead size varied, because different welders used different speeds.

The trend of increasing fatigue strength with decreasing tangent angle shown in Fig. 7 is probably affected to some extent by the tensile strength of the welds. Figure 8 shows a plot of fatigue strength vs. weld tensile strength for the same welds. A general increase in fatigue strength with inincreasing tensile strength is evident in the graph. The rate of increase (slope of the lines) decreases somewhat as the fatigue lives become longer, just as the curves in Fig. 7. Apparently the tangent angle and tensile strength each have an effect on bead-on weld fatigue strength, with both effects showing up in both Figs. 7 and 8. Which effect is greater is unknown. Tomlinson and Wood[5] reported, however, that the long-life fatigue strength of bead-on welds is affected little by static strength.

A plot similar to Fig. 7, but showing the relationship between weld tensile strength and tangent angle, appears in Fig. 9. It is reasonable to expect the weld strength to be influenced to some extent by the angle. The resulting plot shows the data in two groups—the high tensile strength welds and the relatively low strength welds. Neither group shows any tendency for the tensile strength to decrease with an increasing tangent angle. The two groups should be considered separately, because 5052 and 5083-6061 welds have inherently lower strengths than the others. Even if they had a tangent angle equal to, or less than, those of the high strength welds, their strength level would be lower.

Figures 10 and 11 compare the axial-stress fatigue results for $R=0$ and 0.5 (5083-to-6061 butt welds only). The data for $R=0$ were also included in Figs. 5 and 6. The other alloys are expected to have S-N curves for $R=0.5$ similar to those shown in these figures.

Several bead-on weldments had conditions that proved detrimental to their fatigue strength. First, one 5083 (5356) weldment had the base metals offset by nearly 25% of the base metal thickness. Offset causes bending stresses when the joint is loaded axially, which superimpose on the load/-area stress. In Fig. 5, the test points for specimens from that weldment are noted. The offset produced a reduction in fatigue strength of approximately 25%. Another weldment had warpage of 2 to 3 deg between the planes of the two base metals. This condition, as in the case of offset, introduces bending stresses under ax-

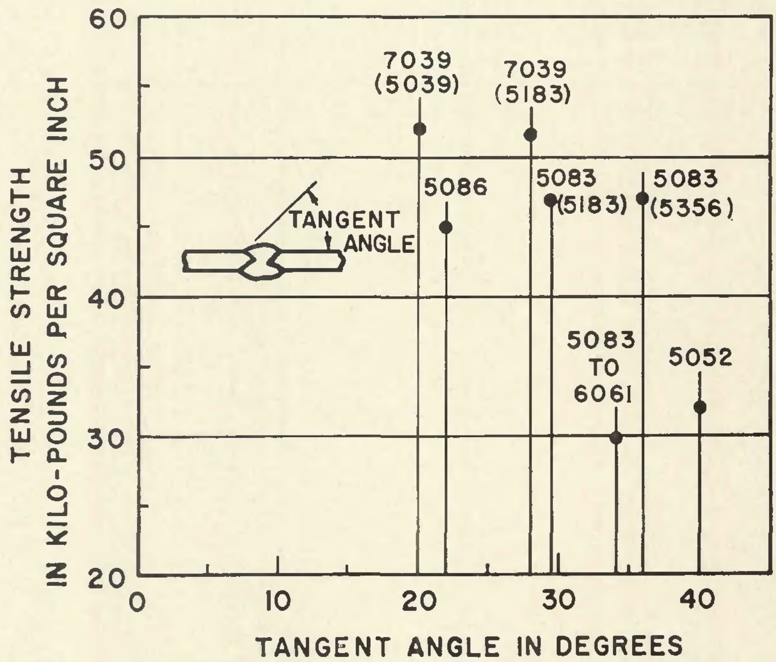

Fig. 9—Butt weld (bead on) tensile strength vs. tangent angle at toe of weld bead (axial stress, R=0)

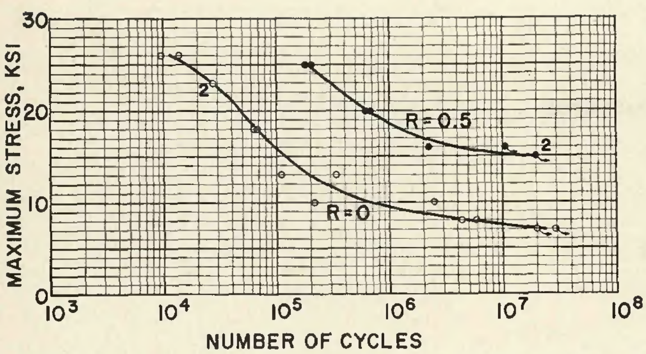

Fig. 10—Axial-stress fatigue S–N curves for 5083 to 6061 butt joints, bead on

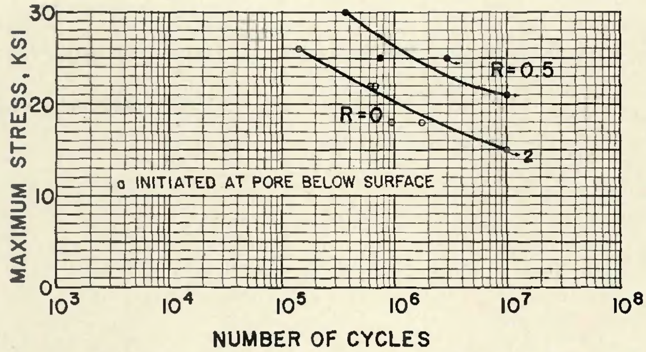

Fig. 11—Axial-stress fatigue S—N curves for 5083 to 6061 butt joints, bead off

ial loads. The warped specimens had a fatigue strength about 1.5 ksi lower than "straight" specimens (Fig. 5). Neither offset nor warpage would be expected to have as large an effect on fatigue strength under repeated-bending fatigue loading.

Figure 12 shows the two fracture surfaces of a butt-joint specimen where weld spatter fell on the toe of the weld. The fracture surfaces revealed that fatigue initiated at that spatter. However, the test point for the specimen fell in line with those of unspattered welds, suggesting that spatter had little effect. Internal defects, such as porosity and dross, apparently had little effect on the fatigue strength of the bead-on welds. Fatigue initiation always occurred at the toe of the welds. Conceivably, the defects could have had an effect, if they had occurred close to the weld toe. Of course, if the defects were so large that cross-sectional area was reduced significantly an effect would be seen.

Although the tensile strengths of the bead-off welds varied considerably for the various alloys, their fatigue strengths were fairly equal (Table 5). The main exception was for alloy 7039 welded with 5039 filler metal. Those welds had, by far, the highest bead-off tensile strength and the highest axial-stress fatigue strength.

If internal defects exist in a weld, they are more apt to affect the fatigue strength of bead-off welds than those of welds with the reinforcement intact. This is because the defects are often exposed on the surface. Even when a defect is not exposed on the surface, it can cause a significant reduction in fatigue strength, as illustrated by Fig. 13. The fatigue strength of that specimen was 2 ksi below the band of data for that alloy (Fig. 6). The effect of dross below the surface is similar. In that case, the fatigue strength was lowered about 3 ksi (Fig. 6).

Figure 14 shows another case where a large solitary pore apparently had a more indirect effect. Since the pore was far from the surface, initiation was not associated with it. The pore did, of course, reduce the net area of the specimen at the cross section, thus increasing the stress somewhat (less than 1%). Apparently, the pore had its greatest effect after fatigue initiated at the surface. The area of fatigue on the fracture surface shown in Fig. 14 is less than half the area on another specimen tested at the same stress level. Apparently, if the pore had not reduced the net area, fatigue crack growth would have continued giving longer total life. The fatigue life of the specimen with the large pore was less than $^{1}/_{10}$th that of the second specimen tested at the same stress (Fig. 6).

Lap Joints in Axial Stress

Double-fillet lap joints had substantially higher tensile strengths than single-filler joints. However, there was generally little difference in fatigue strength between the two joint designs (Table 6). The main difference noted was at the short fatigue lives where the fatigue strength of double-fillet joints was somewhat higher due to their higher tensile strength. The highest fatigue strength was obtained from dissimilar single-fillet joints of $^{1}/_{4}$ in. 6061 and $^{3}/_{8}$ in. 5083 plate, but only when the fillet weld was placed on the edge of the thinner 6061 plate (Fig. 15). When the welds were on the edge of the 5083 plate (requiring larger welds), lower fatigue strengths resulted (apparently due to the lower tensile strength for that condition). In both cases the

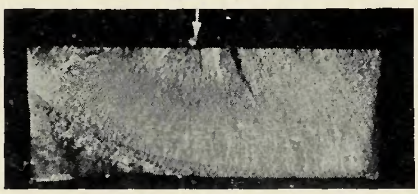

Fig. 12—Fatigue-fracture surfaces of butt weld with spatter at weld toe

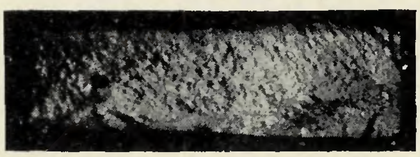

Fig. 14—Fatigue initiation away from 1/16 in. diameter pore located far from surface

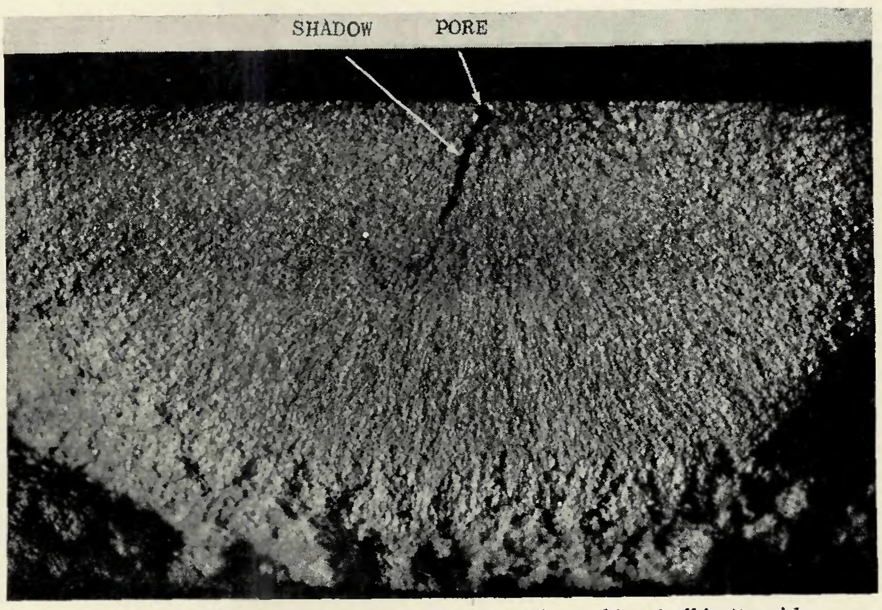

Fig. 13—Fatigue initiation at pore located below surface of bead-off butt weld

Table 6—Axial-Stress Fatigue Strengths of Welded Lap Joints (Stress Ratio, R, Equal to Approximately Zero)[a]

Base metal		Filler	Fatigue strength, ksi, at indicated number of cycles				
Alloy(s)	Thickness, in.	metal	3 × 10³	10⁴	10⁵	10⁶	10⁷
Single fillet:							
5052-H32	3/16	5356	10	7.5	4.5	3	2
5052-H32	3/16						
to 6061-T6	1/4	5356[b]	10	8	5	3.5	2
5083-H113	3/8	5356	10	8	4.5	3	2
6061-T6	1/4						
to 5083-H113	3/8	5356[c]	11.5	8	5	3.5	2
		5356[b]	—	11.5	7	5	3.5
7039-T61	3/8	5039	10	7.5	5	3	1
Double fillet:							
5052-H32	3/16	5356	—	9.5	5.5	2.5	2
5052-H32	3/16						
to 6061-T6	1/4	5356	—	9	4.5	3.5	2
5083-H113	3/8	5356	—	9	4.5	2.5	2
6061-T6	1/4						
to 5083-H113	3/8	5356	—	11	7.5	4.5	2.5
7093-T61	3/8	5039	—	9	5	2.5	1

[a] $R = \frac{S_{min}}{S_{max}}$; S_{min} = 0.15 ksi for all tests.
[b] Fillet weld on edge of 6061 plate.
[c] Fillet weld on edge of 5083 plate.

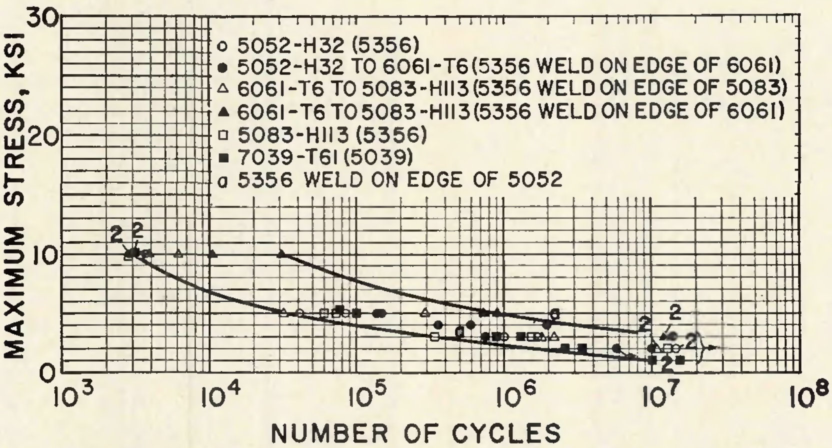

Fig. 15—Axial-stress fatigue data for single-fillet-welded lap joints, R=0

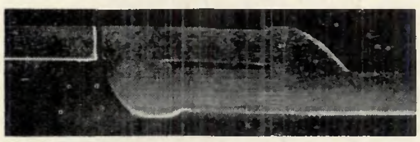

Fig. 16—Dissimilar lap joint of 3/16 in. 5052-H32 and 1/4 in. 6061-T6

stress reported is that in the 6061 plate. The smaller welds (weld on edge of 6061) probably caused less stress concentration than when larger fillets were required.

Figure 16 shows a double-fillet 5052-to-6061 joint with one excessively large fillet weld. Fatigue initiation occurred at the toe of the large weld. The fatigue strength of the specimen was about 30% lower than average for that group (Fig. 17). Figure 16 also shows a substantial gap between the two base metals. Other specimens of this group of joints had similar gaps. Apparently, the gap had no significant effect on the fatigue strength since the data for those specimens fell in line with the other results.

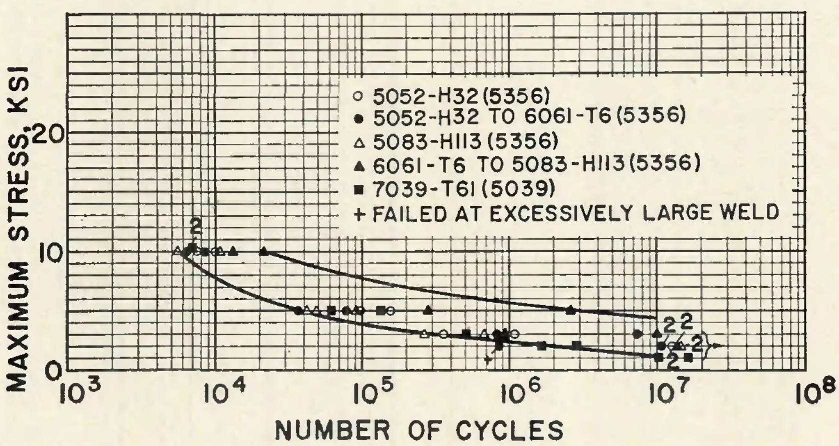

Fig. 17—Axial-stress fatigue data for double-fillet-welded lap joints, R=0

Tee Joints in Axial Stress

The range of data obtained from tee joints is shown in Figs. 18 and 19. Both the tensile strength and fatigue strength of double-fillet tee joints were very substantially higher than those of single-fillet joints (Table 7). Usually the difference between the two joints was more than the factor of two that might be expected by increasing the number of welds from one to two. The main reason double welds gave more than twice the strength is that single-fillet joints are nonsymmetric with respect to the line of axial loading, resulting in large bending stresses.

The highest fatigue strengths for double-fillet tee joints were obtained from joints with unusually large fillet welds. Generally, the weld size (Fig. 1) was about equal to the thickness of the load-carrying member. The 6061 to 5083 and 5083-H321 joints, however, had welds about 20 and 25% larger than normal, respectively (Fig. 20). Another factor that favored the 5083-H321 double-fillet joints was that the surface of the fillet welds blended very gently into the base plates. This low angle reduced the severity of the stress concentration at the weld toe. Contrasted with that, the alloy 7039 joints had fillet welds with somewhat convex surfaces (Fig. 21) which increased the stress concentration. The 7039 joints had the lowest fatigue strength at long lives along with the 5083-H113 joints (Table 7). The latter joints had undersize welds and low tensile strengths.

Weld porosity of moderate size and amount had no apparent effect on the fatigue strength of either the single or double-fillet tee joints. When porosity occurred, it was usually seen at the root of the welds after fracture (Fig. 21). Fatigue usually initiated at the root in the single-fillet joint. On the other hand, the double-fillet joints failed from the root of the welds only in the case of the undersize 5083-H113 welds. The interface between the two base metals made such a sharp notch at the root of the weld that the incidence of porosity probably added little to the stress concentration at the root. The porosity at the root of the welds may have acted to blunt the sharp interface notch. Several cases were found where double-fillet joints had porosity at only one of the two weld roots. In such cases, fatigue usually initiated at the nonporous root. More severe porosity would probably have a detrimental effect on fatigue strength by reducing the cross sectional area.

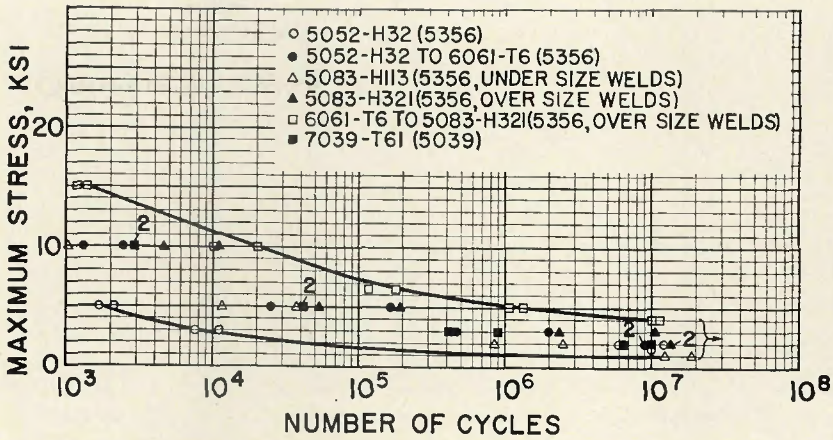

Fig. 18—Axial-stress fatigue data for single-fillet-welded tee joints, R=0

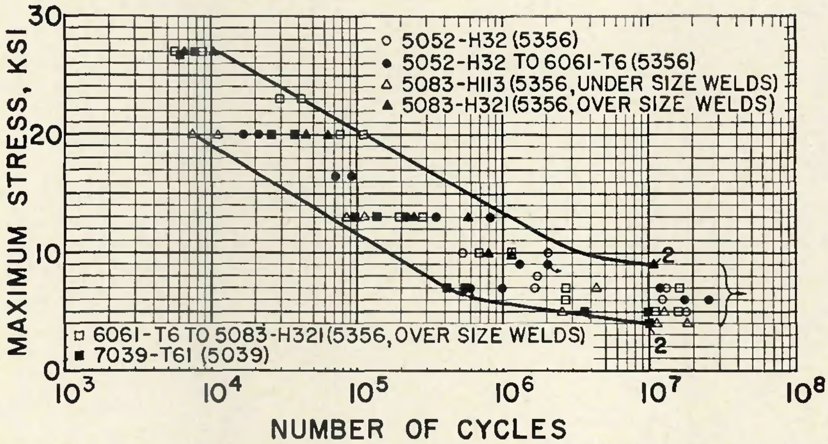

Fig. 19—Axial-stress fatigue data for double-fillet-welded tee joints, R=0

Butt Joints in Repeated Bending

The fatigue strength (repeated bending) of 5083, 5456 and 7039 butt welds with the weld beads on were generally very similar when all the welds had about the same size weld reinforcements (Table 8). The 7039-T61 (5039) welds with low-profile beads (bead height about 13% of plate thickness) had fatigue strengths at least 25% higher than the other welds with larger reinforcements (bead heights of 20 to 30% of plate thickness). Figure 24 shows cross-sections of the two groups of 7039 welds. At high stress levels (and

Table 7—Axial-Stress Fatigue Strengths for Welded Tee Joints (Stress Ratio, R, Equal to Approximately Zero)[a]

Base Metal: Alloy(s)	Base Metal: Thickness, in.	Filler	Fatigue strength, ksi, at indicated number of cycles: 3×10^3	10^4	10^5	10^6	10^7
Single fillet:							
5052-H32	3/16	5356	5	3	2.5	2	2
5052-H32 to 6061-T6[b]	3/16, 1/4	5356	9.5	7	4.5	3	2
5083-H113	3/8	5356	8.5	6	3.5	2	1
5083-H321	3/8	5356[c]	—	9	5	3.5	2.5
5083-H321 to 6061-T6[d]	3/8, 1/4	5356[c]	14	11	7	5	4
7039-T61	3/8	5039	11	7	4	2.5	2
Double fillet:							
5052-H32	3/16	5356	—	—	—	10	6
5052-H32 to 6061-T6[b]	3/16, 1/4	5356	—	21.5	16	8	6
5083-H113	3/8	5356	—	19.5	13	7.5	4.5
5083-H321	3/8	5356[c]	—	26	17.5	10	9
5083-H321 to 6061-T6[d]	3/8, 1/4	5356[c]	—	26	19.5	8.5	5.5
7039-T61	3/8	5039	—	25	14	6	4.5

[a] $R = \frac{S_{min}}{S_{max}}$; S_{min} = 0.15 ksi for all tests.
[b] 5052 sheet is loaded member, see Fig. 1.
[c] Fillet welds oversize.
[d] 6061 plate is loaded member, see Fig. 1.

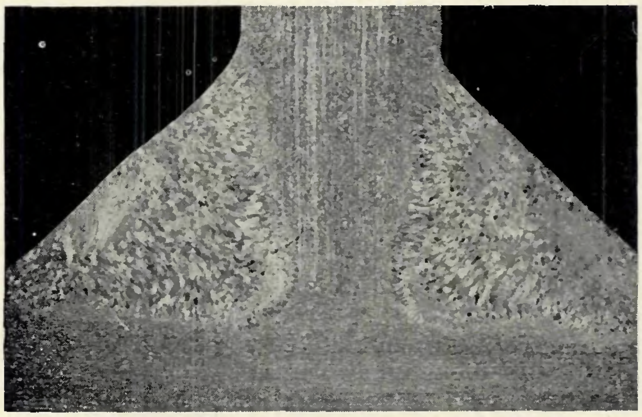

Fig. 20—Alloy 5083-H321 tee joint with oversize fillet welds

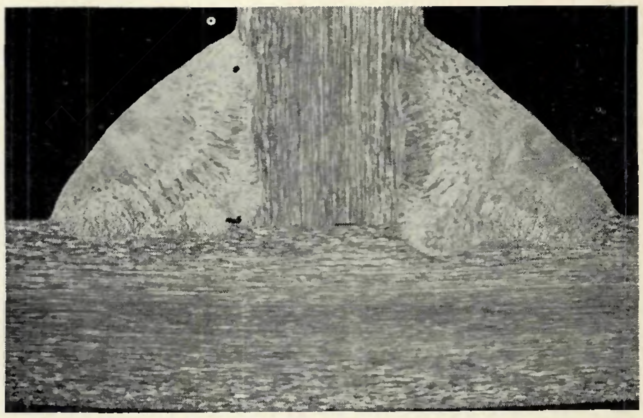

Fig. 21—Alloy 7039-T50 tee joint with porosity and oversize fillet welds

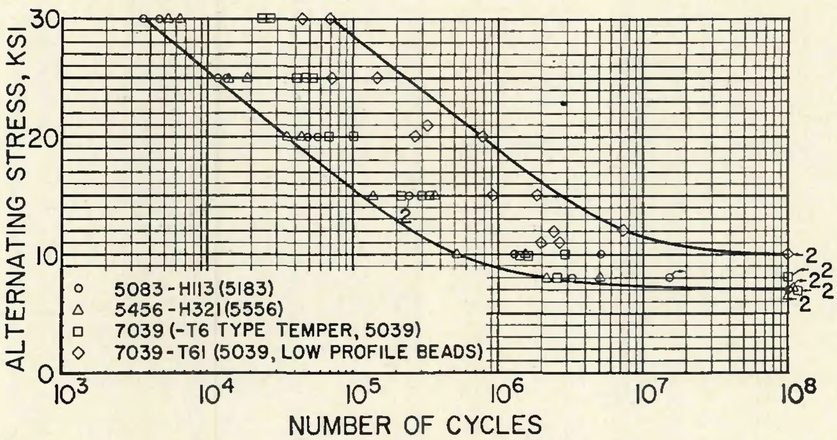

Fig. 22—Repeated-bending fatigue data for bead-on butt joints

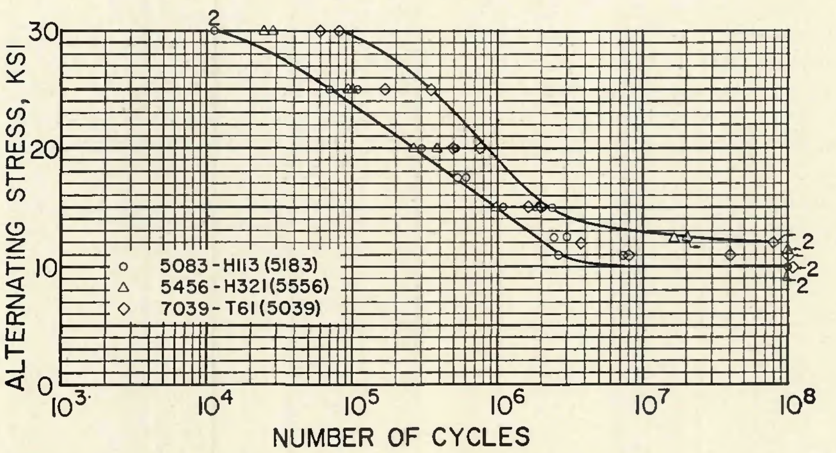

Fig. 23—Repeated-bending fatigue data for bead-off butt joints

short life) the 7039-T6 welds with the larger weld beads also had a substantial advantage over the other two alloys (Table 8 and Fig. 22). The bead-on tensile strengths of all these welds were quite similar (Table 4).

In the bead-off condition (Fig. 23), alloy 7039 (5039) welds had an advantage over the other materials at fatigue lives of one million cycles and less. At longer lives alloy 5456 had slightly higher fatigue strength.

Conclusion

The data presented here demonstrate that the fatigue strength of aluminum alloy welded joints are affected foremost by the geometric characteristics of the joints. The base metal and filler metal alloys play a secondary role, if recommended alloys and practices are followed. In the first place, the fatigue strength is inversely related to the complexity of the joint design. The butt joint with the reinforcement removed is of course the simplest design and has the highest fatigue strength. In this simple case, a base filler metal alloy combination with high tensile strength, such as 7039 (5039), will give above-average fatigue strength. This also applies to welds in the bead-on condition. As the complexity of the welded joint increases (with increased stress concen-

Table 8—Repeated-bending Fatigue Strengths of Welded Butt Joints (Stressed Transverse to Weld Axis)

Base metal[a]	Filler	Fatigue strength, ksi at indicated number of cycles 10^4	10^5	10^6	10^7	10^8
Bead-on:						
5083-H113	5183	26	18	11.5	8	7
5456-H321	5556	28	16.5	9.5	7.5	7
7039-T61 (low-profile beads)	5039	—	25	16	10.5	10
7039 (—T6 type temper)	5039	>35	19	11.5	8	7
Bead-off:						
5083-H113	5183	30.5	24.5	16	10.5	10
5456-H321	5556	33	25	15.5	13	11.5
7039-T61	5039	—	28	17.5	12	10.5

[a] All materials were 3/8 in. thickness.

tration and decreasing symetry), the fatigue strength decreases. Thus, the joints are ranked in order of decreasing fatigue strength as follows:

1. Butt, bead off.
2. Butt, bead on.
3. Tee, double fillet.
4. Lap, double fillet.
5. Lap, single fillet.
6. Tee, single fillet.

The differences in fatigue strength between the last three designs listed were only slight.

The highest fatigue strength for welded tee joints was achieved by using oversize fillet welds (double fillet) that blends smoothly into the base plates. A similar effect could probably be attained by beveling the butting member of the joint before welding to give deeper weld penetration (with smoothly blending welds, also). Large fillet welds with a convex shape lower the fatigue strength of both lap and double-fillet tee joints.

Other physical conditions that have significant effects on fatigue strength include surface and internal defects (which give added stress concentrations) and alignment of base metals

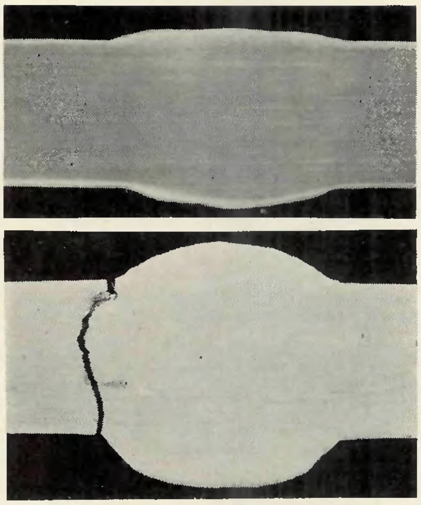

Fig. 24—Alloy 7039 (5039) butt welds with low and high-profile reinforcements tested in repeated bending. A (top)—7039—T61 (5039) weld; B (bottom)—7039-T6 (5039) weld

(offset in butt joints and warpage in all joints superimpose bending stresses). The proven practice of placing welds away from stress concentrations gives added assurance of good fatigue resistance. An example of this in a tee connection is to replace the welded joint with a tee-shaped extrusion and to then butt weld the connecting plates to the extrusion.

References

1. Frost, N. E., and Denton K., "The Fatigue Strength of Butt Welded Joints in Low-Alloy Structural Steels," *British Welding Journal,* Vol 14, April 1967, pp 157-162.
2. Koziarski, J., "Fatigue Aspects in Aircraft Welding Design," Welding Journal, 34 (5), 446 to 458. (1955).
3. Newman, R. P., "Fatigue Strength of Butt Welds in Mild Steel," *British Welding Journal,* Vol 7, March 1960, pp 169-178.
4. Sanders, W. W., Jr., Derecho, A. T., and Munse, W. H., "Effect of External Geometry on Fatigue Behavior of Welded Joints," Welding Journal, 34(2), Research Suppl. 49-s to 55-s (1965).
5. Tomlinson, J. E., and Wood, J. L., "Factors Influencing the Fatigue Behavior of Welded Aluminum," *British Welding Journal,* Vol. 7, April 1960, pp 250-264.
6. Trufyakov, V. I., Asaulenko, L. L., and Koryagin, Yu A., "Stress Concentration in Butt Joints," *Avto. Svarka,* No. 10, pp 19-21 (Translation published by British Welding Research Association).
7. Wilson, W. M., et al, "Engineering Experiment Station Bulletin No. 327, University of Illinois, 1941.
8. Wood, J. L., "The Flexural Fatigue Strength of Butt Welds in NP.5/6 Type Aluminum Alloy," *British Welding Journal,* Vol 7, May 1960, pp 365-380.
9. Navrotskii, D. I., "The Strength of Welded Joints," Mashgiz, Kiev, 1961.

USSR Welding Research News

(*Continued from page* 76-s)

transformers with magnetic cummutation described by the authors are superior with respect to dependability, cost and to the nature of the secondary voltage curve. The consumption of active materials is only 20-30% higher than for unregulated transformers.

• Ignat'ev, V. G. et al.: Filler wire for welding 01915 alloy high-strength Al alloy (57-60).—The effect of 23 different filler wires with different contents of zinc, magnesium, manganese, zirconium, titanium, chromium, iron and silicon of the susceptibility to hot cracking, mechanical properties and corrosion cracking of welded joints in 01915 alloy was studied.

• Chvertko, A. I. et al.: Classification of electron beam welding equipment (61-66).—A classification scheme is proposed which divides EB equipment into three classes according to the degree of protection of the weld metal against the action of atmospheric air. Each class is divided into groups according to the field of application and the size of the workpiece, and each group into subgroups according to degree of specialization. Examples are given for each class, group and subgroup.

• Mirkin, A. M. and Erikhov, A. V.: Machines for the seam welding of flat, stamped, serpentine heat exchangers (67-69).—The design of two new machines developed by VNIIESO is described. The optimum operating conditions for welding the contour seams and the seams between the channels in the heat exchanger panels of domestic refrigerators is described.

Avtomaticheskaya Svarka 23, No. 8 (August 1970)

• Mechev, V. S. and Eroshenko, L. E.: Determination of the plasma temperature of an arc discharge in argon (1-6).—The true temperature of the argon plasma was determined by different spectral methods and the causes of the fluctuations of this temperature were examined.

• Nikolaev, G. A.: Welding and cutting of organic tissues (7-10).—A method for the ultrasonic welding, overlaying and cutting of human bone, shin and muscle tissue has been developed and used under clinical conditions. The advantages of the use of ultrasonics over the conventional mechanical methods are pointed out.

• Dzhevara, I. I. et al.: Investigation of the fusion zone in welded joints between carbon steel and aluminum bronze (11-14).—The diffusion layer in the fusion zone between carbon steels and aluminum bronze has been investigated.

• Lankin, Yu. N. et al.: Heating of the working surfaces of the electrodes in multipulse resistance welding (15-18).—The effect of the operating papameters of multipulse spot welding on the temperature of the working surfaces of the electrodes was studied by means of an electrical model. The results were verified experimentally by resorting to a statistical method of planning the experiment.

• Kravstov, T. G.: Method of selecting the operating conditions for weld surfacing cylindrical workpieces with a strip electrode (19-22).—A method for selecting the operating variables for overlaying cylindrical workpieces with a strip electrode is described. With the proper conditions, the shape of the deposit is improved and the slag removal is facilitated.