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FATIGUE STRENGTH OF WELDS IN LOW-ALLOY STRUCTURAL STEEL

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FATIGUE STRENGTH OF WELDS IN LOW- ALLOY STRUCTURAL STEELS

Experimental program shows that, for all types of specimens tested, there is little difference in the fatigue strengths of the several low-alloy steels

BY J. E. STALLMEYER, G. E. NORDMARK, W. H. MUNSE AND N. M. NEWMARK

SUMMARY. Fatigue tests have been conducted on full-scale butt welds and fillet welds in low-alloy steel plates with the stress applied either parallel to or perpendicular to the direction of welding. Several different steels meeting the ASTM designation A-242 were used in this investigation to study the uniformity of results of different steels meeting this specification.

The fatigue strengths of steels meeting the requirements of ASTM designation A-242 do not differ appreciably in spite of the comparatively wide variations in their chemical compositions. Further, the presence of the weld in the steel reduced the magnitude of the variations between the average fatigue strengths of the different alloy steels.

A comparison of the fatigue strengths of joints in the low-alloy steels with the fatigue strengths of similar joints prepared from A-7 steel with E7016 electrodes is also included in the paper.

Introduction

Object and Scope of Investigation

Since the introduction of low-alloy steels for structural purposes, the question has often been asked—on what physical property or properties should the design stress for these steels be based? The answer depends, of course, on the type of loading applied to the material when it is assembled into members and structures and also the factor of safety desired against the possible modes of failure. Originally there was some contention that all design stresses should be based on the yield point of the material; however, investigations have proved that under some conditions, such designs might have an extremely low factor of safety against failure. Such may be the case when members are subjected to repeated loads for it has been shown that the endurance limit of a steel member is not necessarily related directly to the yield point of that steel. Further, Professor W. M. Wilson [1-3] found that the presence of a welded or riveted joint in a steel having a high yield point might reduce the fatigue strength of the joint so that it is little, if any, greater than that of ordinary A-7 steel. The susceptibility of low-alloy steel to fatigue failures has, in many instances, precluded the use of this material for structures which are subjected to repeated loadings.

Relatively few fatigue tests have been conducted on welded joints in steels other than those meeting ASTM Specification A-7. The results of the tests by Wilson indicated that butt-welded joints in one low-alloy steel had a fatigue strength about 20% higher than similar joints in A-7 steel whereas the difference in yield points was about 50%. With advances in welding techniques and materials, such as the development of the low-hydrogen electrode, and also improvements in the properties of the low-alloy steels, it is desirable to determine if the fatigue strength of welded joints in low-alloy steel might have been improved enough to make the use of such materials economical in structures subjected to repeated loadings.

Description of Steels

The steel plates used in this investigation were ordered to comply with the ASTM Specification for A-242 steel. The chemical analyses and physical properties of the different steels are given in Tables 1 and 2. According to the mill tests, steel P and steel T also meet the military specification for Mil (S) 12505, Grade 1 and steel Q meets the military specification for Mil (S) 12505, Grade 5.

The tensile coupons from steel T

Table 1—Chemical Composition of Steel Plate

Steel	*Chemical content, %**								
	C	*Mn*	*P*	*S*	*Si*	*Cu*	*Ni*	*Cr*	*Vq*
A-7	0.17	0.68	0.016	0.039	0.03	...	...	...	...
P	0.12	0.56	0.106	0.043	0.32	0.45	0.46	0.61	...
T	0.20	1.08	0.010	0.025	0.10	0.38	0.60	...	...
Q	0.19	1.10	0.022	0.028	0.25	0.43	...	...	0.04

* Check analysis.

Table 2—Physical Properties of Steel Plate, Standard 8-In. Gage Length Tensile Coupon

Steel	*Yield strength, psi*	*Tensile strength, psi*	*Elongation in 8 in., %*	*Reduction of area, %*
A-7 (Average)	33,300	57,400	33	62
P (Average)	56,800	76,700	25	53
(Mill report)	57,600	81,700	24	..
T (Average)	47,800	73,600	27	58
(Mill report)	51,300	76,900	26.5	..
Q (Average)	53,100	77,600	26	49
(Mill report)	55,300	82,900	24.5	..

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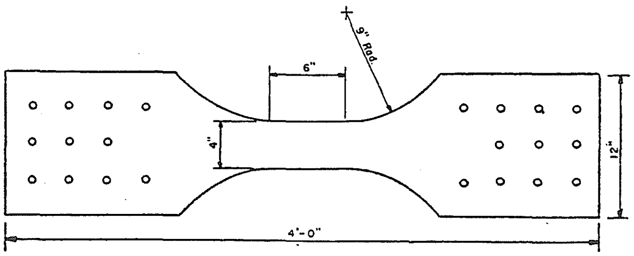
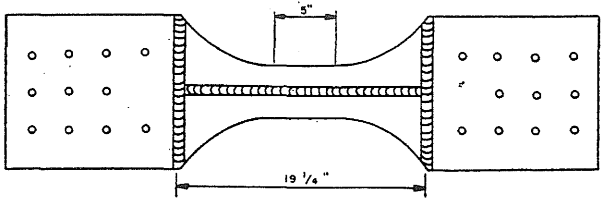
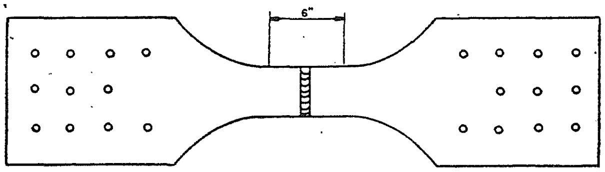


a. PLAIN PLATE

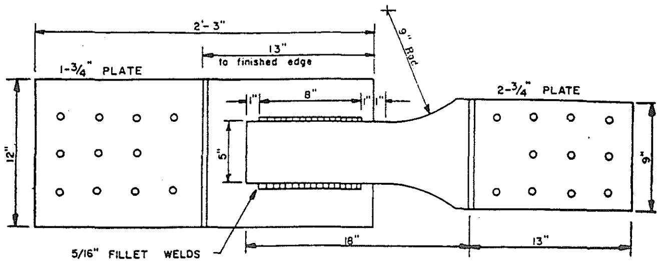


b. LONGITUDINAL BUTT WELD

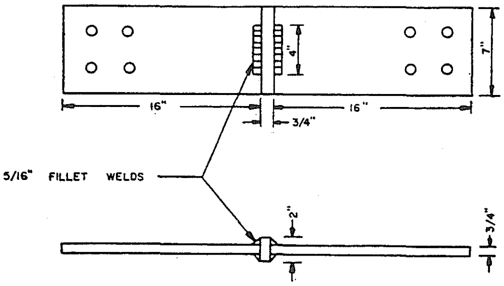


c. TRANSVERSE BUTT WELD

Fig. 1 Details of butt-welded joints



a. LONGITUDINAL FILLET-WELDED JOINT



b. TEE FILLET-WELDED JOINT

Fig. 2 Details of fillet-welded joints

did not meet the minimum requirements for yield point, 50,000 psi, although the mill tests indicated an acceptable strength. Steels P and Q met both the physical and chemical requirements.

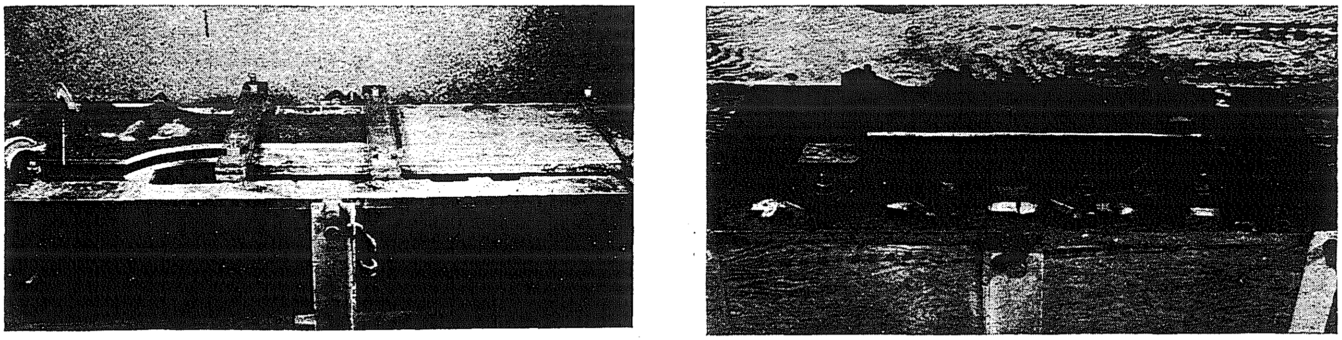
Preparation of Butt-Welded Joints and Plain Plate Specimens

Typical dimensions of the plain plate specimens and the butt-welded joints are shown in Fig. 1. For all of these specimens the test section was 4 in. wide but the test section varied in length for the different materials. This variation in length of the straight section was necessary because of the limited amount of material available and the resulting necessity of welding heads of other steel to the test section of the low-alloy steel. The weld joining the test section to the heads had to be large enough to prevent failure in this weld.

The plates for the transverse butt welds were flame cut from the parent plate with an increased width at the joint to enable the start and the end of the weld to be removed from the specimen later by machining. In preparation for welding, the plate was saw-cut at the joint and the joint machined in a shaper to provide for a double-V butt weld having an included angle of 60°.

In order that each of the six weld passes could be deposited in the flat position, the two plates were securely clamped to a welding jig, as shown in Fig. 3, which could be rotated about a horizontal axis. Before the clamps of the jig were tightened, the root opening was set at $^1/_8$ in. The first two passes were deposited with $^5/_{32}$ in. diam electrodes and all remaining passes with $^3/_{16}$ in. diam electrodes. Mil 180 electrodes were used for the T and Q steels whereas E7016 electrodes were used for the P steel. In previous tests it had been found that the slag was much easier to remove from welds produced with the Mil 180 electrode.

After deposition of the first pass, the weld was back chipped to expose sound base metal. Ten minutes of air cooling was allowed between the first and second passes for the transverse butt welds and 15 min for the longitudinal butt welds. Cooling periods of 5 min were used between succeeding passes. The specimens were air cooled after deposition of the last pass. The welding sequence was such that a change of electrode occurred in the test section in each pass of the weld, adjacent passes were welded in opposite directions, and changes of electrode in adjacent passes did not occur one over the other. The



(a) Jig in position for second pass, longitudinal fillet weld

(b) Jig in position for second pass, longitudinal butt weld

Table 3—Welding Procedures

Pass	Steel	Electrode	Diam., in.	Open circuit voltage, V	Current, amp	Voltage, V	Burn off rate, ipm.	Rate of travel, ipm
Longitudinal fillet welds								
All	P	E7016	$^{3}/_{16}$	73	190	21	8.4	6.1
Tee fillet welds								
All	P	E7016	$^{3}/_{16}$	73	185	20	4.8	9.1
Longitudinal butt welds								
1	P	E7016	$^{3}/_{16}$	73	170	20	7.9	4.6
2–6	P	E7016	$^{3}/_{16}$	73	185	20	8.6	5.7
1	T, Q	Mil 180	$^{5}/_{32}$	72	135	20	9.0	3.5
2	T, Q	Mil 180	$^{5}/_{32}$	72	160	21	9.7	4.8
3, 4	T, Q	Mil 180	$^{3}/_{16}$	72	210	22	9.8	6.6
5, 6	T, Q	Mil 180	$^{3}/_{16}$	72	200	22	9.6	6.1
Transverse butt welds								
1	P	E7016	$^{3}/_{16}$	72	160	20	7.7	4.2
2–6	P	E7016	$^{3}/_{16}$	72	180	20	8.4	4.0
1	T, Q	Mil 180	$^{5}/_{32}$	73	140	20	9.3	3.0
2	T, Q	Mil 180	$^{5}/_{32}$	73	160	21	9.5	4.2
3, 4	T, Q	Mil 180	$^{3}/_{16}$	73	210	22	10.0	6.4
5, 6	T, Q	Mil 180	$^{3}/_{16}$	73	200	22	9.2	5.0

welding power was supplied by a 200-amp d-c rectifier-type welder. The electrodes were operated at the current and voltage levels, given in Table 3, which were measured on portable meters connected as close to the arc as possible. After completion of the welding, the specimens were machined to the dimensions shown in Fig. 1 and the edges were draw filed.

For those specimens tested with the weld reinforcement and mill scale removed, a portable grinder was employed to remove the reinforcement, mill scale, and surface defects. The grinding was started with a 36 grit wheel and finished with a 120 grit wheel in such a manner that the final scratches were parallel to the direction of loading.

The preparation of the longitudinal butt welds was in all respects similar to that used for the transverse weld specimens except that the test weld was prepared first for the longitudinal specimen. This test section was then prepared to provide for a double-V butt weld which joined the test section to the pull heads. As a part of this process the start and the finish of the test weld was removed from the completed specimen. This precaution was taken to reduce the possibility of failure in the transverse weld.

Preparation of Tee Fillet-Welded Joints

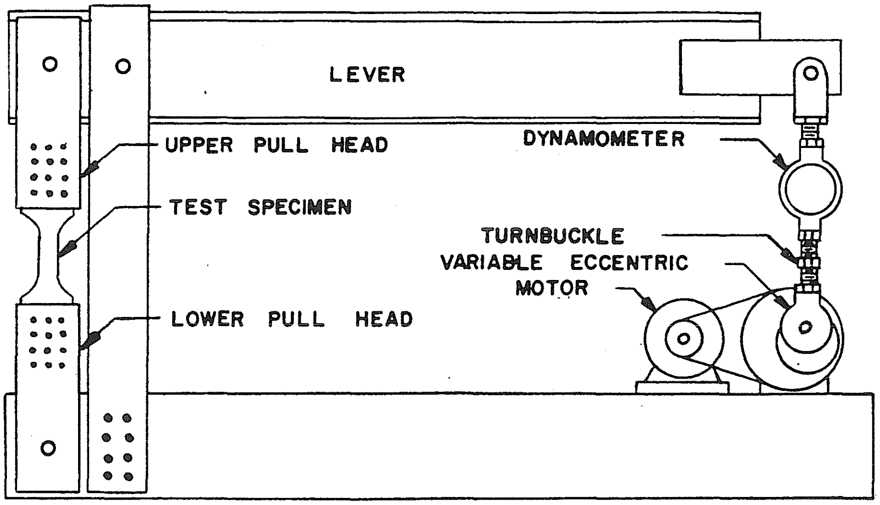
The tee-fillet specimens were composed of two 7- x $^{3}/_{4}$- x 16-in. longitudinal plates which were welded to a 2- x $^{3}/_{4}$- x 7-in. transverse tee plate. To prepare the longitudinal plates for welding, one end of each plate was machined perpendicular to the plane of the plate and the mill scale was ground off the areas of the plate where the weld was to be deposited. In order to remove the mill scale and surface was machined to a depth of 0.025 in. Uniform spacing between the longitudinal plates was maintained by the use of paper spacers consisting of eight thicknesses (0.027 in.) of No. 20 bond paper.

A 4-in. long, single pass, $^{5}/_{16}$-in. fillet weld was manually deposited in each intersection of the joint using the welding procedures given in Table 3. Each weld was deposited with a single E7016 electrode and the direction of welding was alternated for succeeding welds. A cooling period was allowed between welds to secure an interpass temperature of less than 200° F.

Preparation of Longitudinal Fillet-Welded Joints

As shown in Fig. 2, the test section of this specimen consisted of a 12-in. x $^{3}/_{4}$-in. x 2-ft. 3-in. center plate joined by two 5-in. x $^{3}/_{4}$-in. x 2-ft. 7-in. outside plates with four 8-in. long, single pass, $^{5}/_{16}$-in. fillet welds. The design stresses were approximately equal for the weld and outside plates; a stress of 12,800 psi in the outside plates corresponding to a stress of 13,600 psi on the throat of the weld.

The 8 in. length of the single-pass fillet weld required a change of electrode which was made at the mid-point of the weld. The direction of the welds was different for the two welds on one face of the specimen. During the 45-sec interval between the deposition of each electrode on one face of the specimen, the end of the weld was cleaned. A 15-min cooling period was used before welding was initiated on the second face in order that the temperature of the weldment would be 150° F or less. After completion of the welds, the specimen was allowed to air cool for at least 10 min before being removed from the welding jig.



Test Procedures

The fatigue tests were performed at room temperature in two 200,000-lb capacity W. M. Wilson lever-type fatigue machines which operate at a speed of approximately 200 cpm. Because one of the machines was not equipped to apply a compressive load, it was necessary that a tension be applied to the specimen at all times to insure that the bearings would be properly seated throughout the tests. Accordingly, the stress cycle employed in the present tests was one which varied from a low tension of about 6000 lb to a maximum tension; however, this loading will be referred to as a zero-tension cycle.

The essential features of the machine, shown in Fig. 4, are a variable throw eccentric which transmits force through a dynamometer (for determining the load on the specimen) to a lever which in turn transmits the load to the upper pull head at a multiplication ratio of approximately 15 to 1. The double throw eccentric is adjusted to give the desired range of load before the test is begun. The maximum load is set by means of an adjustable turnbuckle mounted between the eccentric and the dynamometer. The stress is determined by a mechanical dial which indicates the vertical deflection across the throat of the dynamometer to the nearest 0.001 in.

After a specimen had been bolted in the fatigue machine, a stress equal to the maximum desired stress was first statically applied to the specimen. Plastic straining occurred for those specimens to be tested above their yield points. For these specimens it was necessary to allow sufficient time for the specimens to strain under the maximum load before the load could be maintained under repeated loadings.

The fatigue machines were run continuously. A microswitch stopped the machine when the maximum deformation of the specimen increased. The load was checked frequently at the start of the test, but later only as often as necessary to maintain the desired load. Failure is defined as having occurred when the fatigue crack was large enough to actuate the microswitch and stop the machine. This was generally found to be a crack about 1 $^1/_2$ in. long.

One specimen of each type was tested statically in a 600,000-lb Riehle testing machine at a strain rate of 0.10 ipm for the plain plate and butt-weld specimens and 0.05 ipm for the longitudinal fillet-welded joint.

Evaluation of Fatigue Tests

In order to numerically compare the results of fatigue tests of specimens tested at different stress levels, fatigue

Table 4—Results of Fatigue Tests of Plain Plate Specimens

Specimen	Stress, psi	Cycles to failure, 10^3	Fatigue strength $f_{100,000}$, psi	Fatigue strength $f_{2,000,000}$, psi	k
		A-7 Steel			
H10	35,500	1508.0	...	35,200	0.18
H46	40,000	450.3	...	33,000	0.18
H49	37,000	1078.3	...	34,100	0.18
H58	37,200	1627.2	...	36,200	0.18
			Avg	34,600	
		Steel P			
P2	50,000	126.4	51,300	36,900	0.11
P3	50,000	198.5	53,900	38,800	0.11
P4	50,000	249.4	55,300	39,800	0.11
		Avg	53,500	38,500	
		Steel T			
T2	45,000	1787.2	...	44,400	0.11
T3	50,000	409.6	58,400	42,000	0.11
T5	46,200	696.0	57,200	41,100	0.11
		Avg	57,800	42,500	
		Steel Q			
Q1	50,000	224.2	54,600	...	0.11
Q2	48,000	304.6	54,300	39,100	0.11
Q3	49,100	384.6	57,000	41,000	0.11
		Avg	55,300	40,000	

Table 5—Results of Fatigue Tests of Longitudinal Butt-Welded Joints

Specimen	Stress, psi	Cycles to failure, 10^3	Fatigue strength* $f_{100,000}$, psi	Fatigue strength* $f_{2,000,000}$, psi
		A-7 Steel, E6010		
H7	40,100	86.0	39,300	...
H19	30,000	451.7	36,400	24,700
H77	30,000	417.4	36,200	24,400
H79	36,000	89.2	35,600	...
H91	29,600	304.5	34,200	23,300
H97	40,000	123.0	41,100	...
H103	36,000	180.6	38,900	...
		Avg	37,400	24,100
		A-7 Steel, E7016		
H9	40,000	184.0	43,400	...
H74	29,500	751.1	...	26,000
H88	30,000	447.3	36,700	24,800
H90	39,500	177.3	42,600	...
H98	30,000	1223.7	...	28,200
H100	40,000	207.7	44,000	...
		Avg	41,700	26,300
		Steel P		
P12	40,000	374.0	50,700	29,600
P13	40,000	350.2	50,200	29,200
P15	41,000	186.9	45,800	...
P16	34,000	844.1	...	29,100
P17	34,000	768.0	...	28,600
P18	34,000	321.0	42,000	24,500
		Avg	47,200	28,200
		Steel T		
T12	40,000	229.2	46,500	...
T15	40,000	145.1	42,700	...
T16	40,000	216.8	46,000	...
		Avg	45,100	
		Steel Q		
Q9	40,000	145.1	42,700	...
Q10	40,000	141.1	42,600	...
Q11	41,400	118.7	41,300	...
		Avg	42,200	

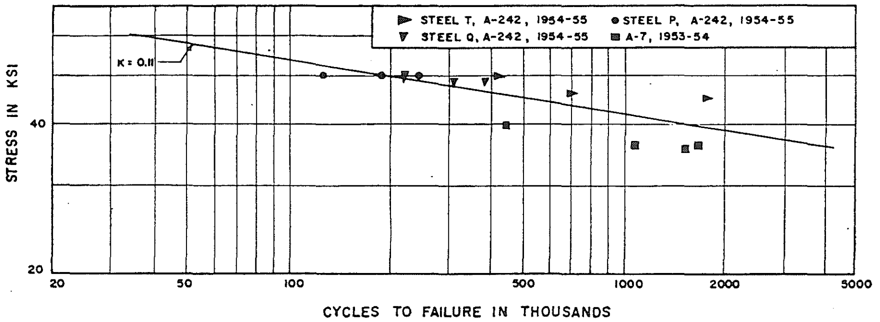


Fig. 5 Results of fatigue tests of plain plate specimens tested with the mill scale on

100,000 and 2,000,000 cycles have been computed from the formula[1] $f = S(N/n)k$, where S is the test stress at which the specimen failed after N cycles, n is the number of cycles for which the fatigue strength, f, is desired, and k is an experimental constant determined from the slope of the median plot on the S-N diagram. For those specimens having a fatigue life greater than 2,000,000 cycles, the value of S has been used as the fatigue strength at 2,000,000 cycles.

Generally, if the number of cycles to failure was less than 600,000, this data was used to compute the fatigue strength for failure at 100,000 cycles; if the value of N was greater than 300,000, the fatigue strength was computed for failure at 2,000,000 cycles. For specimens failing between 300,000 and 600,000 cycles, both fatigue strengths were computed.

Test Results

Fatigue Tests of Plain Plate Specimens

The fatigue strengths of the various alloy steels and of an A-7 steel when tested in plain plate specimens are presented in Table 4 and Fig. 5. Typical failures of plain plate specimens are shown in Fig. 6. As would be expected from the tensile coupon yield strengths, specimens T3 and T5 yielded when their maximum loads were applied statically. Although the coupon tests indicated a yield strength for the Q steel of more than 51,000 psi, specimen Q3 began yielding within the first 1000 cycles of loading. In addition, after 1,224,000 cycles of loading at a stress of 45,000 psi, specimen T2 began to yield.

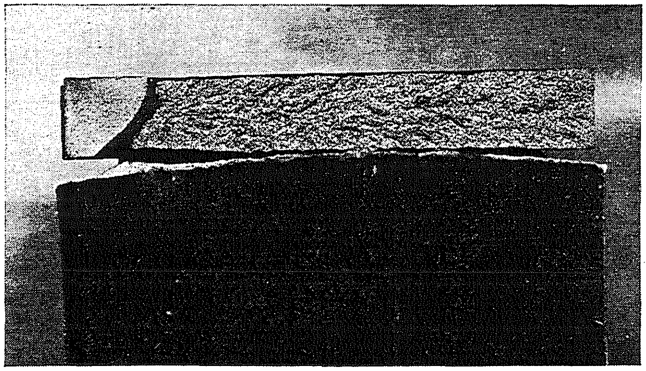
The scatter of results of the Q steel was less than that of the T and P steels, and, although the scatter bands of all three steels overlap, the T specimens generally had the longer fatigue lives.

The average fatigue strengths of the T and Q specimens were about 9 and 3% higher, respectively, than that obtained from steel P. It appears that the low-alloy steels have average values of $f_{2,000,000}$ from 10 to 25% higher than the A-7 steel. However, the yield strengths of the low-alloy steels were about 45 to 75% higher.

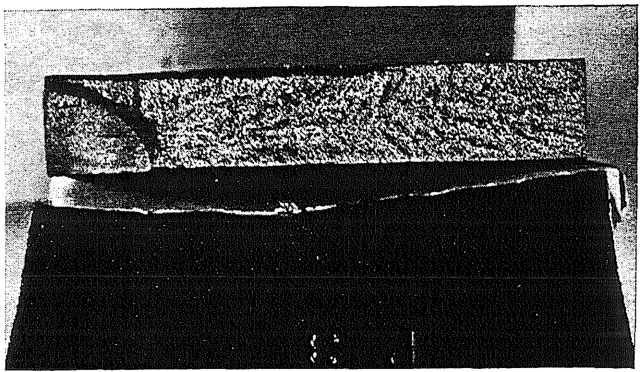
Fatigue Tests of Longitudinal Butt Welds

The results of the fatigue tests of the longitudinal butt welds are presented in Table 5 and in Fig. 7. All of the specimens reported herein were tested in the as-welded condition. All of the failures initiated in a region where the electrode of a surface pass had been changed. Although there are some variations in the metallurgical properties at a change of electrode as a result of a short period of air cooling and the subsequent arc strike, it would appear that the cause of failure was primarily geometrical, because a notch-type discontinuity of some severity is formed perpendicular to the direction of the applied stress wherever a new electrode is started. Typical fractures of the longitudinal butt-welded specimens are shown in Fig. 8.

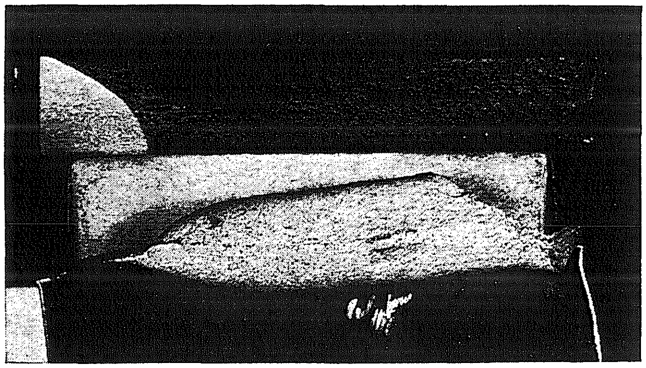
As may be seen in the S-N diagram,



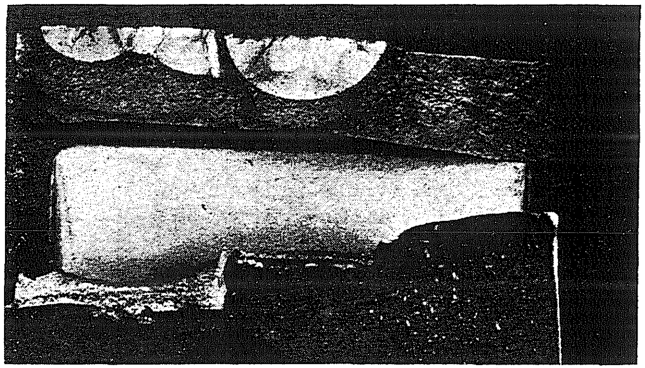
H-49



P-3



T-2



Q-3

Fig. 7, the Q specimens exhibited very little scatter but had the lowest fatigue lives of the three low-alloy steels tested; generally, the fatigue lives of the T specimens lie between those of the Q and P specimens. These trends are also apparent in the fatigue strengths reported in Table 5. Using a value of $k = 0.18$, the average fatigue strengths of the longitudinal butt welds of steel P were 10 and 4% higher, respectively, than those of steels Q and T for $f_{100,000}$.

Fatigue data obtained from the 1953–54 series of longitudinal butt-welded joints in A-7 steel are also plotted with the results of the low-alloy steel tests in Fig. 7. The scatter bands of the A-7 specimens overlap those of the Q and T specimens and, in fact, the average fatigue strength of the A-7 steel welded with the E7016 electrode is almost as high as that of the Q steel. Accordingly, the average fatigue strengths of the longitudinal butt welds in low-alloy steel vary from 1 to 12% greater than those of the A-7 joints prepared with E7016 electrodes and 13 to 20% greater than those of the A-7 joints prepared with E6010 electrodes. Thus the use of the E7016 electrodes for the joints of A-7 steel made the advantage of the low-alloy steel negligible.

Table 6—Results of Fatigue Tests of Transverse Butt-Welded Joints

Specimen	Stress, psi	Cycles to failure, 10^3	—Fatigue strength*— $f_{100,000}$, psi	$f_{2,000,000}$, psi
		A-7 Steel, E6010		
H12	29,400	537.9	36,600	24,800
H14	28,000	539.4	34,900	23,600
H22	26,000	802.2	...	23,100
H26	35,000	95.3	34,800	...
H32	26,300	984.0	...	24,000
H48	36,000	53.2	33,200	...
H54	25,000	1695.4	...	24,500
		Avg	34,900	24,000
		A-7 Steel, E7016		
H13	29,100	354.8	34,300	23,200
H17	39,000	117.8	39,800	...
H21	26,000	1097.0	...	24,000
H25	39,600	98.8	39,600	...
H31	24,200	1243.8	...	21,800
H65	25,700	3056.2	...	25,700+
		Avg	37,900	23,800+
		Steel P		
P5	37,000	73.5	35,700	...
P6	30,000	493.9	36,900	25,000
P7	29,000	556.5	36,300	24,500
P9	37,000	221.0	41,000	...
P10	36,900	349.0	43,300	29,400
		Avg	38,600	26,300
		Steel T		
T6	37,000	177.5	39,900	...
T7	37,000	113.8	37,500	...
T8	30,000	608.8	...	25,700
T9	37,000	331.2	43,200	29,300
T10	30,000	825.6	...	26,700
T11	30,000	507.1	37,000	25,100
		Avg	39,400	26,700
		Steel Q		
Q5	37,000	172.0	39,700	...
Q6	37,000	133.5	38,400	...
Q7	36,700	190.5	40,000	...
		Avg	39,400	

* $k = 0.13$.

Fatigue Tests of Transverse Butt Welds

Table 6 presents the results of fatigue tests on the transverse butt-welded joints. These results are shown graphically in Fig. 9. In spite of the changes in the welding procedure [use of electrodes meeting military specification Mil-E-986-A (Mil 180), smaller diameter electrodes for the root passes, and a larger root opening], five of the six transverse butt welds of steel T failed internally from slag inclusions, or other flaws, in the weld metal. However, it was noted that fatigue cracks had also initiated at the edge of the weld of one of these specimens. One joint did fail at the edge of the weld, but after the specimen was pulled apart statically a small fatigue crack was also found in the weld metal.

For the Q specimens a higher interpass temperature was used. In spite of this fact and the more meticulous inspection of each pass for slag, one of the Q joints failed from an internal defect. Further, when the specimens were statically pulled apart, it was found that, of the two Q specimens failing at the edge of the weld, one had an internal defect visible in the fracture surface. Typical fracture surfaces of the transverse butt-welded joints are shown in Fig. 10.

The *S-N* diagram, Fig. 9, shows that the results of the tests of Q specimens did not have nearly as much scatter as those of the P and T specimens. However, the scatter bands of the three low-

extent so that there appears to be little, if any, advantage for any one of the steels. The same conclusion is apparent in the data included in Table 6. The T and Q joints had values of $f_{100,000}$ which were only 2% higher than those of the P joints.

The low-alloy steels had fatigue strengths which averaged about 12% higher than those of the previous tests of plain carbon steel when the latter specimens were welded with E6010 electrodes. However, when E7016 electrodes were used with the A-7 steel, the advantage of the A-242 joints was reduced to only 2 to 5%. This situation might be improved slightly by the use of techniques which would insure the elimination of failures in the weld metal. However, the occurrence of fatigue

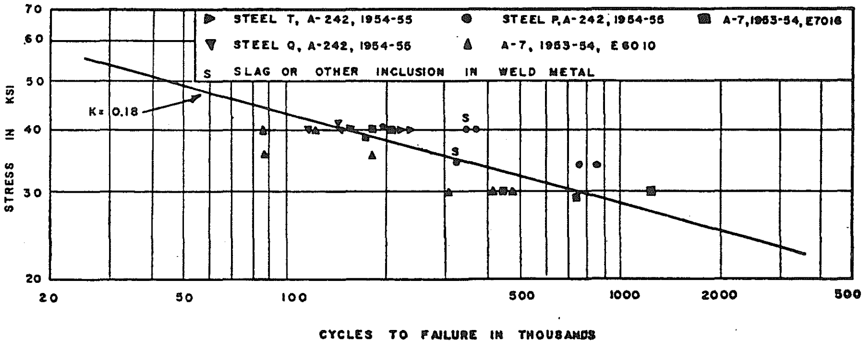
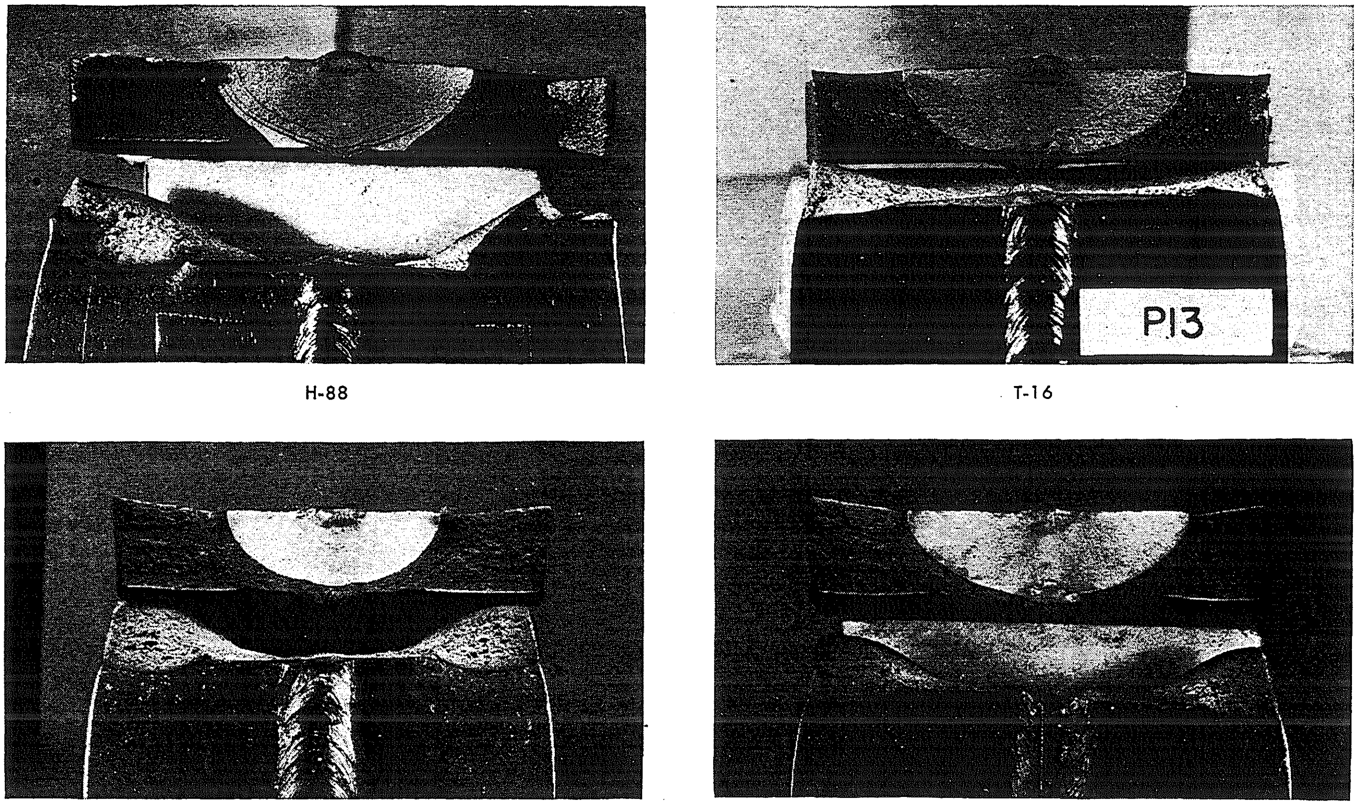


Fig. 7 Results of fatigue tests of longitudinal butt-welded joints tested in the as-



H-88

T-16

P-13

Q-9

Fig. 8 Typical fractures of longitudinal butt welds

cracks at the edge of one of the welds that failed from an internal defect, plus the fact that the specimens which failed at the edge of the weld had fatigue strengths not more than 5% greater than the joints which failed internally, makes it appear that only a negligible increase in fatigue strength would accompany the elimination of the internal failures unless such measures also improved the fatigue resistance at the edge of the weld.

It is apparent then that the A-7 transverse butt welded joints prepared with E7016 electrodes are practically as good as the joints fabricated from A-242 steel.

Fatigue Tests of Longitudinal Fillet-Welded Joints

Five of the longitudinal fillet-welded specimens, subjected to repeated loading, failed in the outside plates at the end of the weld as indicated in Fig. 11. The sixth specimen had a fatigue crack through the throat of one weld as well as a crack in the outside plate at the end of the weld on the opposite face of the specimen. However, it appears that the initial failure occurred in the plate. Four of these failures initiated in the plate from the crater end of a weld and two from the strike end.

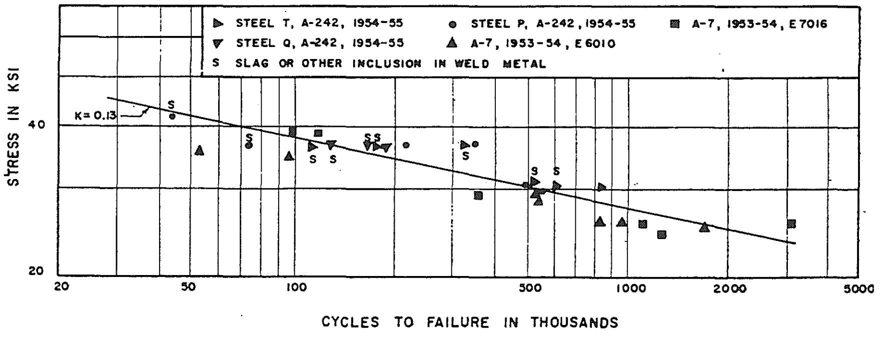
The *S-N* diagram, Fig. 12, shows that the specimens tested on the higher stress cycle, 0–20,000 psi, exhibited with the lower stress cycle show a considerable amount of scatter. The fatigue strengths for failure at 100,000 cycles are given in Table 7.

It is difficult to make a direct comparison between the present results and those obtained in previous tests since the specimens are of different geometry. The data presented in Table 8 indicate that there were two series of tests, namely V and W, which gave extremely low values of fatigue strength. Study of the variables presented in this table reveals that these specimens differ from the others in several respects. The ratio of nominal stress in the weld to nominal stress in the plate is quite high. Also, the ratio of plate width to weld length is very high. Consequently any correlation of the fatigue strengths with nominal stresses is questionable.

It is likely that the geometry as well as the nominal stresses plays a very important role in joints of this type. More tests than are reported here are required to resolve fully this problem. However, on the basis of the available data it appears that the average fatigue strength of the low-alloy specimens may be slightly higher than would have been obtained from similar specimens of A-7 steel.

Fatigue Tests of Tee Fillet-Welded Joints

The fatigue cracks of the tee-fillet specimens occurred in the weld metal on a line approximately through, or slightly on the tee-plate side of, the throat of the weld. An examination of the fatigue cracks, after failure, and an examination of the fracture surfaces, after the specimens were pulled apart statically, indi-



cated that most of the fatigue failures did not initiate at the ends of the weld. It is difficult to determine the point of origin of the failure in a fillet weld as the fatigue failures generally spread along the length of the weld with little indication as to the sequence of failure. Typical fatigue cracks and fracture surfaces shown in Fig. 14 indicate that the fracture surface consisted of two distinct regions; a fairly smooth, planar, surface having an angle less than 45° from the tee plate and a rough fibrous appearing surface having an angle greater than 45° from the tee plate.

In no case does the smooth portion, the region of initial fatigue fracture, extend to the surface of the weld. The rougher portion must, therefore, contain the final stages of the fatigue failure as well as the static fracture. From the similarity of the static region with part of the fatigue region, it would seem that the rate of propagation of the fatigue fracture increased when the plane of failure changed.

In the tests of A-7 steel, it was noted that many of the welds which failed in fatigue also separated slightly from the longitudinal plate. This phenomenon was especially noticeable after the welds had been pulled apart statically. However, no such separation was noted in any of the tests in the low-alloy steel. The absence of the separation in the present tests could be due to the fact that the mill scale had been removed from the longitudinal plate in the region of the weld whereas it was not in the tests of A-7 steel.

The values of stress, reported in Table 9 and Fig. 13, have been computed from the external area. As may be seen from the *S-N* diagram, both series exhibited a considerable amount of scatter.

The fatigue strengths have been computed from the test data using a value of $k = 0.25$, selected from previous tests. The average fatigue strength for failure at 2,000,000 cycles is the same for both steels but the fatigue strength for failure at 100,000 cycles is 500 psi greater for the welds in A-7 steel. It would appear that the fatigue properties of welds made with the E7016 electrode are approximately the same in either steel.

Conclusions

The following conclusions are based on the results of the experimental program discussed herein.

1. For all types of specimens tested there was little difference in the fatigue strengths of the several low-alloy steels, although the results of steel Q generally exhibited less scatter than those of steel P and T

Table 7—Results of Fatigue Tests of Longitudinal Fillet-Welded Joints

Specimen	Stress, psi	Cycles to failure, 10^3	Fatigue strength*: $f_{100,000}$, psi	$f_{2,000,000}$, psi
		Steel P		
P26	20,000	175.6	23,400	...
P27	14,500	1018.3	27,800	12,000
P28	14,000	298.4	19,000	...
P29	20,000	162.8	22,900	...
P30	14,000	225.6	17,600	...
P32	20,000	185.9	23,600	...
		Avg	22,400	

* $k = 0.28$.

Table 8—Average Results of Past and Present Fatigue Tests of Longitudinal Fillet-Welded Joints Tested on a Zero to Tension Stress Cycle and Failing in the Plates

Series	Electrode	Plate width, in.	Weld length, in.	A_w Area of weld metal in.^{2}	A_{pl} Area of plate in.^{2}	$\frac{S_w}{S_{pl}}$[a]	$f_{100,000}$[b]
			A-242 Steel				
P, 1954–55[c]	E7016	5	8	7.07	7.50	1.062	22,400
			A-7 Steel				
1953–54[c]	E6010	6	7	6.19	4.50	0.728	21,500
1953–54[c]	E7016	6	7	6.19	4.50	0.728	22,700
T, Bull. 350	[d]	4	4	4.24	3.00	0.707	21,000
U, Bull. 350	[d]	6	4	4.24	4.50	1.063	20,100
V, Bull. 350	[d]	9	4	4.24	6.75	1.58	14,200
W, Bull. 350	[d]	9	4	4.24	6.75	1.58	15,300
EZ, Bull. 350	[d]	9	$10^1/_2$	11.13	6.75	0.690	21,600
Z, Bull. 350	[d]	9	10	10.60	6.75	0.636	18,900

[a] $\frac{S_w}{S_{pl}} = \frac{A_{pl}}{A_w}$.

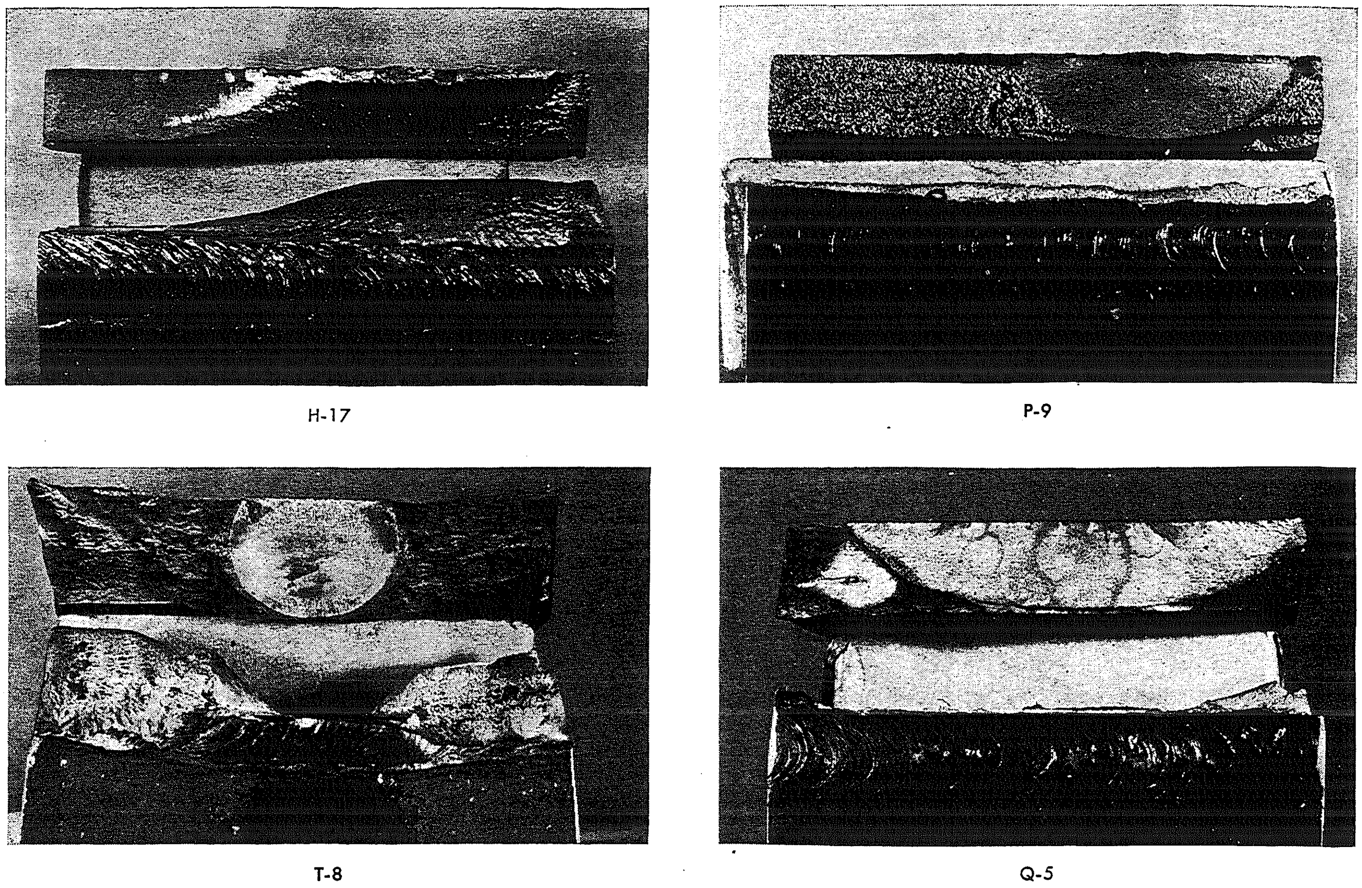
[b] $k = 0.28$.

[c] See Bibliography, Reference 5.

[d] Electrode not specified.

Table 9—Results of Fatigue Tests of Tee Fillet-Welded Joints Welded with E7016 Electrodes

Specimen	Stress, psi	Cycles to failure, 10^3	Fatigue strength*: $f_{100,000}$, psi	$f_{2,000,000}$, psi
		A-7 Steel		
H34	14,900	400.4	21,100	10,000
H36	20,000	280.3	25,900	...
H38	20,100	243.9	25,100	...
H66	20,000	175.4	23,000	...
H68	14,800	538.1	22,600	10,600
H80	11,900	1837.1	...	11,600
H82	20,000	780.4	...	15,700
H84	13,100	4665.3	...	13,100
H86	12,000	4319.4	...	12,000
		Avg	23,500	12,200
		Steel P		
P19	13,900	668.1	...	10,600
P20	13,000	2568.3	...	13,000+
P21	13,000	1758.2	...	12,600
P22	20,000	330.2	27,000	12,800
P32	20,000	183.1	23,300	...
P24	20,000	75.2	18,600	...
		Avg	23,000	12,300+


H-17

P-9

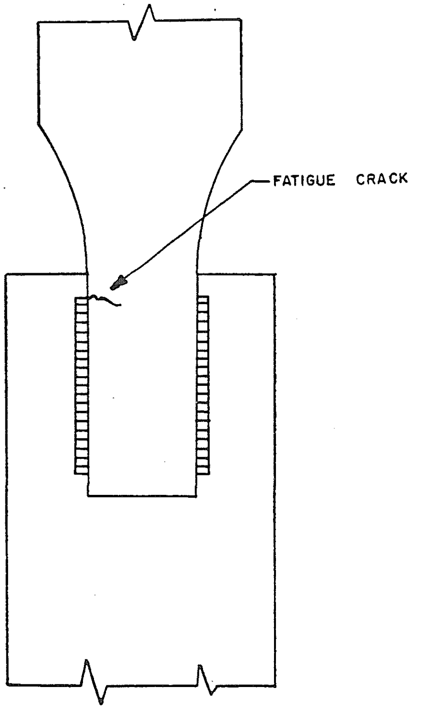
T-8

Q-5

Fig. 10 Typical fractures of transverse butt welds

plain-plate specimens of the low-alloy steels exhibited an increase in fatigue strength over that of the A-7 steel of from 10 to 25%. The yield strength was, however, from 45 to 75% higher for the low-alloy steels.

3. The average fatigue strength of longitudinal butt-welded joints in the low-alloy steels were from 13 to 20% higher than those of A-7 joints prepared with the standard E6010 electrode. The use of the E7016 electrode for the



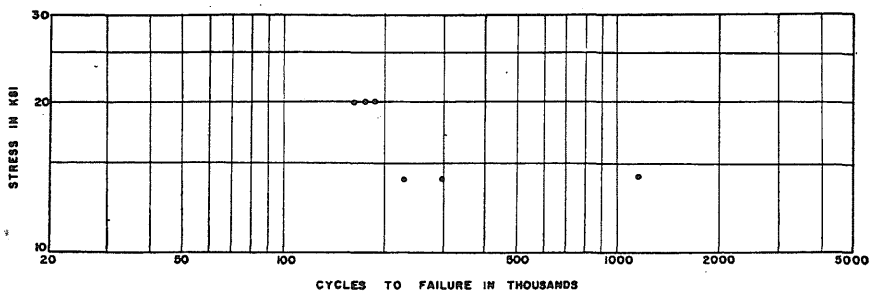


Fig. 12 Results of fatigue tests of longitudinal fillet-welded joints, Steel P, A-242

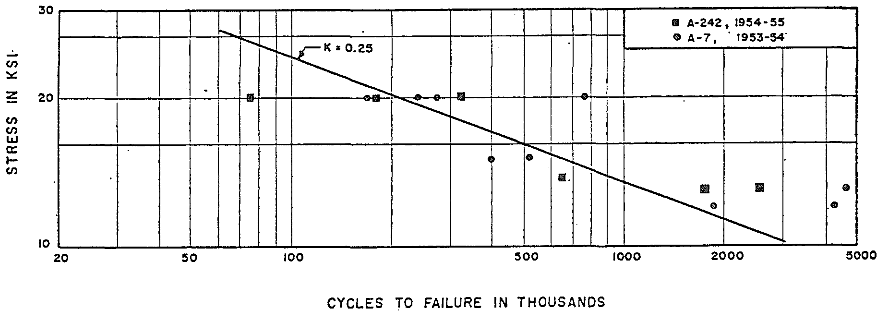
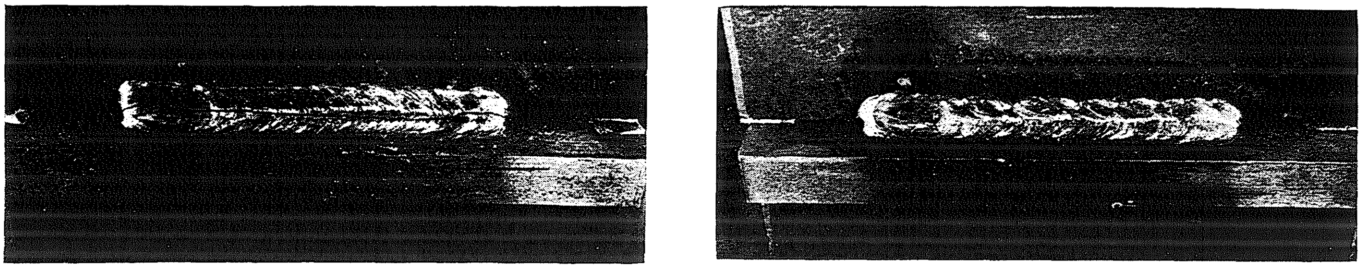


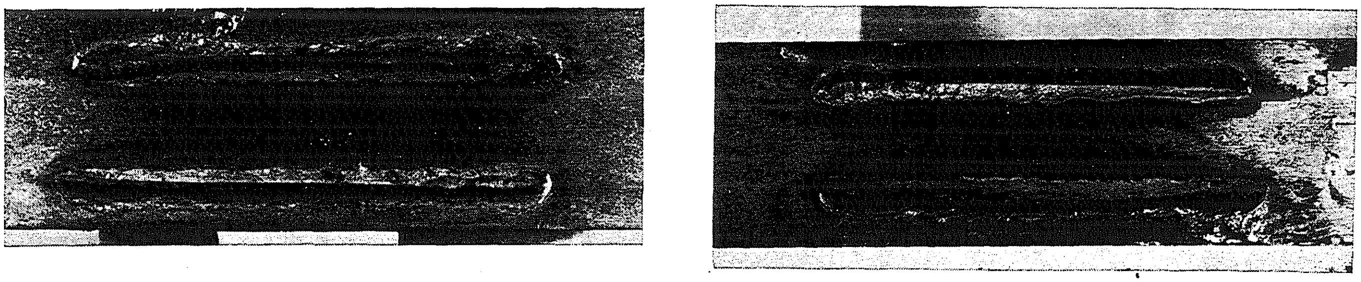
Fig. 11 Sketch of location of fatigue failure in longitudinal fillet-welded

Fig. 13 Results of fatigue tests of tee fillet-welded joints welded with E7016



P-20 P-19

(a) Fatigue cracks



P-20 P-21

(b) Fracture surfaces

Fig. 14 Fatigue failures of tee fillet-welded joints

A-7 joints reduced the advantage of the low-alloy specimens to less than 10%.

4. For transverse butt-welded joints the advantage of the A-242 specimens was about 10% when the A-7 joints were welded with E6010 electrodes but less than 5% when E7016 electrodes were used for the A-7 joints.

5. The tests of the tee fillet specimens showed that the E7016 electrode produced weld metal having approximately the same fatigue strength when used for fillet welds in either A-7 or low-alloy steels.

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