WELDING RESEARCH

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The Toughness and Fatigue Strength of Welded Joints with Buried Lamellar Tears

Techniques are developed for producing partial lamellar tearing in a T-joint and for controlling the extent and location of tearing with respect to the weld toe

BY E. J. KAUFMANN AND R. D. STOUT

ABSTRACT. In a previous investigation at Lehigh University sponsored by the AISI, it was shown that the susceptibility of steels to lamellar tearing was significantly affected by the hydrogen potential of the welding process and that properly executed surfacing is an effective remedy to avoid tearing. When lamellar tears reach the surface, they can be repaired, but if there are buried tears they may go undetected. The question then is what is the effect of their size on the fatigue strength and toughness of the welded joint. This question was addressed in the present project by tests on an A572 steel shown to be susceptible to lamellar tearing.

Techniques were developed for producing lamellar tears of various sizes in the Lehigh cantilever test specimen under the weld toe or at the weld root. Under R = O loading, it was found that the fatigue strength measured at 1,000,000 cycles of life was reduced more than the area loss due to the size of the flaw. For example, a tear under the weld toe equal to 5% of the weld section reduced fatigue strength by 17%, and a tear of 30% lowered the fatigue strength by 45%. When the lamellar tear was located near the weld root, the effect was considerably lessened, as might be expected under the bending mode of cycling.

The same specimen design was used to measure the toughness and load-carrying capacity of the welded joint when loaded at a strain rate equivalent to that occurring in bridges. A series of specimens containing a range of tear sizes was tested through the fracture transition temperature range. Again the effect of the tear was magnified compared to its size. It must also be noted that the toughness and load-carrying ability of the welded joint in the lamellar tear-sensitive A572 steel was also limited even when completely free of lamellar tears.

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Introduction

In a series of investigations (Refs. 1-3) conducted at Lehigh University under the sponsorship of the American Iron and Steel Institute, a testing method was developed for measuring quantitatively the sensitivity of structural steels to lamellar tearing and determining the influence of welding conditions on the tendency for tearing. In a recent study (Ref. 4) the following results were obtained:

1. Each heat of steel exhibits an inherent sensitivity to lamellar tearing, which can vary considerably from the surface to the mid-thickness of the plate and from one plate or part of a plate to another.
2. Of welding conditions, the welding process was found to exert the most significant influence on lamellar tearing. Welds produced by the GMAW process or the submerged-arc welding process were consistently more resistant to tearing than those made with the SMAW or FCAW process. This difference apparently resulted from the presence of hydrogen in the electrodes of the latter two processes.
3. Except for very high levels, heat input appeared to be an unreliable method of influencing the tendency for tearing. No trend was observed in a five-fold range of heat inputs with the GMAW process.
4. Preheating was beneficial to the tearing resistance of GMA welds, but it was especially useful for SMA and FCA welds, counteracting the damaging effects of hydrogen. The use of preheating in actual service structures must be done in a way that does not increase the total contraction of the joint upon final cooling and thus aggravate the tearing strains. In some cases, peening may be helpful in counteracting the contraction strains in the joint.
5. Experiments in which the hydrogen potential in the arc atmosphere was deliberately varied demonstrated clearly the deleterious effect of hydrogen on lamellar tearing resistance. This behavior has been shown for both the GMAW and SMAW processes and for both carbon steel and low-alloy steel plates.
6. The conditions under which buttering is an effective preventative of tearing were established: namely, the use of a buttered region deep enough to move the base metal at least 6 mm (0.23 in.) away from the joining weld and large enough to extend 15 mm (0.59 in.) beyond the toe of the weld.

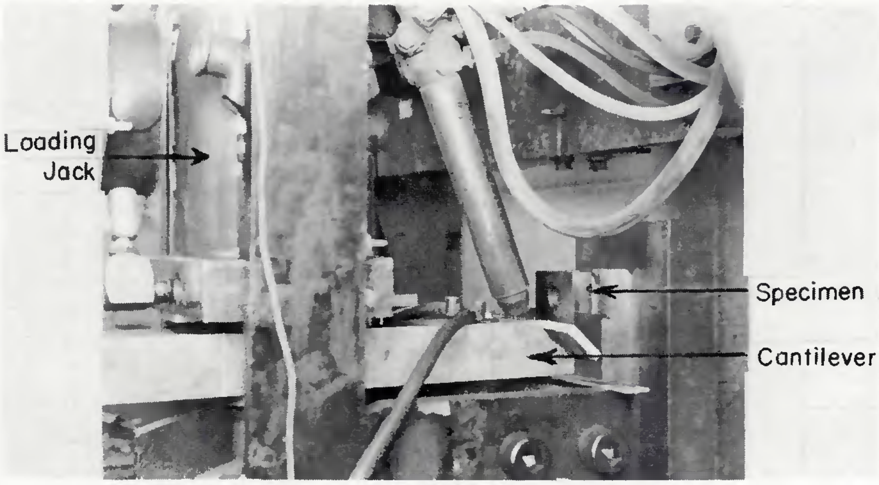

Fig. 1—Cantilever tear test setup

When lamellar tearing is extensive enough to become visible at the welded joint surface, its occurrence is obvious and repair or replacement of the weld can be executed. If the tearing is partial and buried, the inspection may not detect its presence. The purpose of this investigation was to learn how the location and size of lamellar tears would affect the fatigue resistance and dynamic toughness of welded joints. The aim was to establish the size of tear which

mance and to provide a basis for selecting appropriate inspection requirements to be applied to critical (and lamellar-tearing susceptible) welded joints in a service structure.

Experimental Program

Production of Lamellar Tears

The Lehigh cantilever test (Ref. 1) used previously to evaluate sensitivity to lamellar tearing was chosen as a means of producing lamellar tearing under controlled conditions. The cantilever configuration appeared to be convenient for later cyclic or single load testing as well. Figure 1 shows the arrangement of the test specimen and a view of the welding jig. A572 Grade 50 steel found useful in the study of weld conditions was chosen for these tests, again by splitting the plate through its thickness and welding on the midthickness. Table 1 lists the composition and the longitudinal and thru-thickness properties of the steel. It should be noted that the steel tested was chosen because it exhibited a marked susceptibility to lamellar tearing at its midthickness. Control of nonmetallic inclusions by current manufacturing processes readily avoids this condition.

In the initial experiments buried tears were produced by the following procedure. The 76 mm (3 in.) wide specimen and cantilever beam with run-off tabs were joined by a multipass GMA weld deposited at 30 V, 300 A, and 30 cm per minute (11.8 ipm) welding torch travel speed. Nine passes were required to fill the groove. For the series of sound specimens, a small external load was maintained on the cantilever during welding to keep its lower half completely seated against the specimen.

To produce specimens containing buried tears a load stress just below the critical stress known to cause tearing (47 ksi or 324 MPa) was applied while depositing the first 6 passes. After the sixth pass the load was slowly increased until the load began to drop, corresponding to the formation of buried lamellar tears. The load was then quickly released to prevent further tearing. The top three passes were deposited under a nominal load to avoid further tearing. After completion of welding, 13 mm (0.51 in.) of metal was trimmed from each side of the specimen to give a final weld joint area of 12.5 cm^2 (1.94 in^2). At the same time the trimmed pieces provided sections which could be polished and examined to measure the extent of the lamellar tearing.

A satisfactory technique for producing buried lamellar tears was developed. Nonetheless, it was realized that a serious limitation existed in the ability to place the tears at various locations in the joint, especially next to the weld toe where stresses were highest. Loading a completed weld to obtain buried tears was found to be unreliable, because the high loads required tended to bring the tears to the weld surface or even fail the weld before the load could be released.

A more elaborate procedure solved this problem. As Fig. 2 shows diagramatically, three passes were deposited in the groove and the specimen loaded to generate tearing. At this point the specimen was removed from the welding jig and placed in a band saw to make a vertical cut along the original specimen face, leaving a few mm of the weld metal to buffer the tear from subsequent weld penetration. The specimen was then reinserted into the jig, and a new cantilever was positioned. Positioning was such that the upper tip of the buried tear was aligned with the top of the cantilever and thus at the location of maximum fiber stress during cycling. The groove was then filled in the normal fashion with the cantilever held firmly in position but not appreciably loaded.

A further refinement in the specimen preparation was the attachment of an acoustic emission transducer to the cantilever during the weld sequence used to obtain partial tearing. It was found that alternate increments of loading and waiting produced avalanches of signals that tapered off promptly until a critical load was reached, whereupon signals increased rather than faded. Within seconds the load dropped. Thus, the early warning provided by acoustic emission improved the control over the amount of buried tearing.

Fatigue Testing

A fatigue testing machine (Fig. 3) capable of a speed of 3 Hz and loads up to 3600 kg (7937 lb) was modified to apply a load on the top of the cantilever but not in the reverse direction, thus loading the weld from 0 to tension (R = 0). The machine operated with constant deflection, but a screw adjustment was provided to take up any slack between the loading point and the cantilever beam at zero load if the specimen gradually developed a permanent set due to crack growth by fatigue.

Both the load and the deflection of the cantilever were recorded during cycling.

Table 1—Composition and Mechanical Properties of the A572 Grade 50 Steel Used for Tests

Chemical composition, %:		
C 0.18	Si 0.28	Mo 0.04
Mn 1.32	Ni 0.10	V 0.06
P 0.011	Cr 0.13	Cu 0.13
S 0.025		Al 0.034
Mechanical properties:	Longitudinal	Thru-thickness
Yield strength, MPa (ksi)	410 (59.0)	377 (58.2)
Tensile strength, MPa (ksi)	620 (89.0)	522 (75.8)
Elongation in 51 mm (2 in), %	28.5	—
Reduction in area, %	50.0	6.6

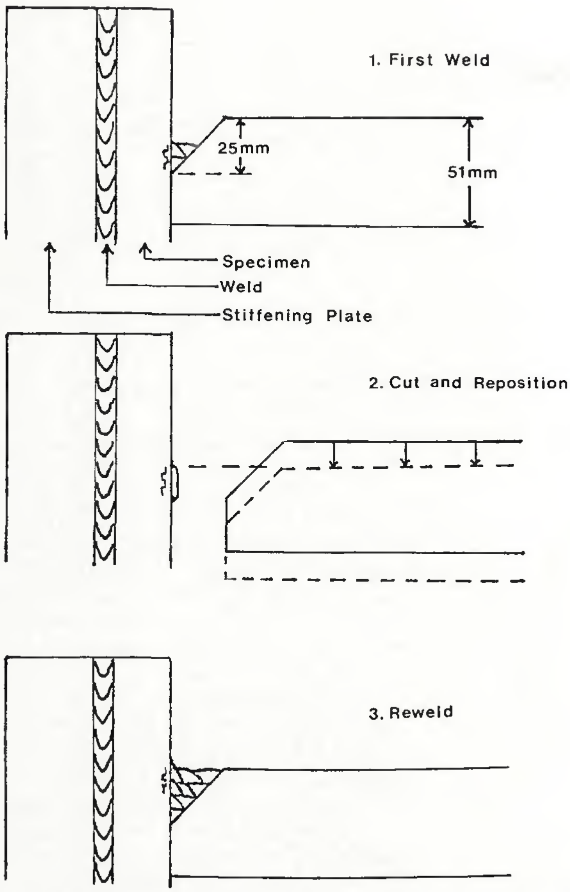

Fig. 2 — Test specimen produced by the cut-and-reweld method

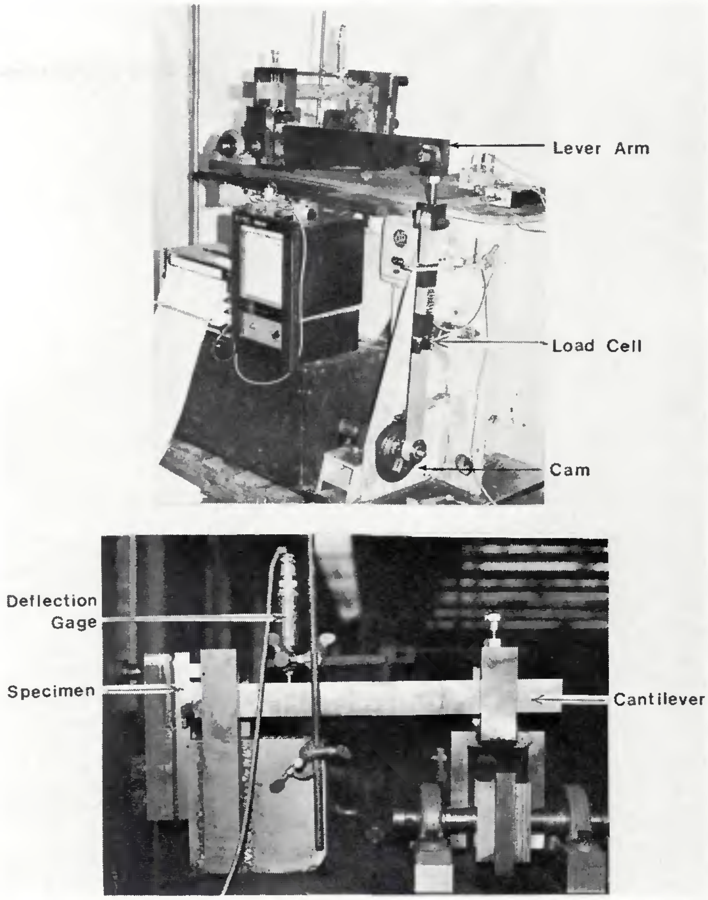

Fig. 3 — Fatigue testing machine

Incipient failure was detected by a decrease in load range and an inelastic increase in average deflection. Several events were observed during a test:

1. The cycles at first visible crack.
2. The cycles at which the load range decreased to 90% of the original range.
3. The cycles for virtually complete failure.

Of these, the cycles for 10% loss of load range were taken as the most significant observation.

It was noticed that a gap of 0.1-0.2 mm (0.004-0.008 in.) tended to open up between the specimen and the beam at the bottom pivot point during unloading. Accordingly, a 6 mm (0.24 in.) lock weld was added at the bottom of the cantilever in a V-groove. Although loading was from the top only, apparently localized plastic strains at the top of the weld during loading caused a rotation of the weld area on an axis within the weld metal that, in turn, generated the gap during unloading. The added metal at the bottom was included in the calculation of the moment of inertia and the maximum fiber stresses during cycling.

After fatigue failure, the specimens were broken open to check the extent of lamellar tearing and the progress of fatigue failure. Sections were also removed for examination by scanning electron microscopy (SEM).

Elevated Strain-Rate Toughness Testing

The cut-and-reweld technique developed for the fatigue test specimens was used to prepare specimens for toughness as well. The testing method was simply to mount the test specimen vertically in a jig so that the cantilever beam could be loaded rapidly to failure of the welded joint — Fig. 4.

The strain rate obtained by loading in a universal testing machine was 0.05/second(s), comparable to loading rates in a bridge structure. A load-deflection curve was recorded in each test, and the series of tests covered the fracture transition temperature range of the A572 steel.

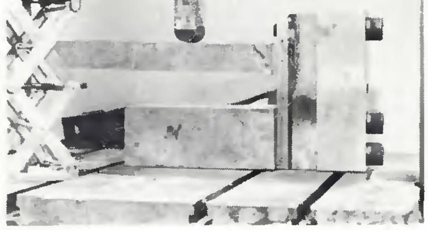

Fig. 4 — Jig setup for elevated strain-rate toughness tests

Results and Discussion

Fatigue Tests

Fatigue test data are recorded in Table 2. In the initial series of fatigue tests, the lamellar tearing was induced in the lower layers of the welded joint, and the fatigue resistance was found to be relatively insensitive to the presence of tears. This can be seen from the results displayed in Fig. 5. This behavior was recognized as due to the bending nature of the cyclic load imposed on the cantilever beam.

When the cut-and-reweld technique was used to move the tear into alignment with the weld toe (close to the maximum tension area), the fatigue resistance was strongly influenced by the presence of tearing. Figure 6 shows that the fatigue strength was lowered more than would be accounted for by the loss in supporting area engendered by the size of the lamellar tear. The quantitative relation is exhibited more clearly in Fig. 7 where it can be seen that a lamellar tear intercepting 5% of the weld area reduced fatigue strength at 10^6 cycles by 17%. The effect lessens at larger tear sizes.

The implication is that tearing reduces fatigue strength by two effects:

1. By reducing the supporting area of the joint.
2. More importantly, by creating a severe stress raiser at the tear tip acting in

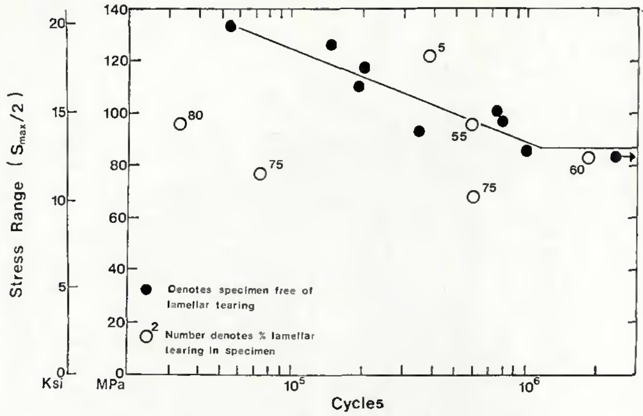

Fig. 5—Fatigue test results on specimens with original weld procedure

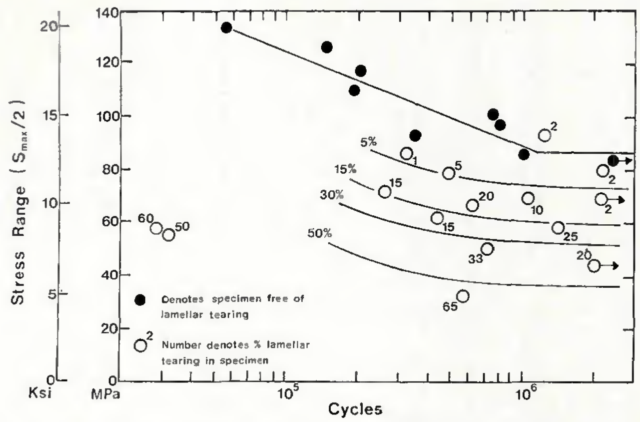

Fig. 6—Fatigue test results on specimens prepared by cut-and-reweld technique

close proximity to the weld toe, which is itself a stress raiser.

Thus, the lamellar tear triggers an earlier initiation of fatigue crack growth. The corollary is that tears located at inner layers of the joint—and, therefore, more distant from the weld toe—cannot initiate fatigue and so exert relatively little effect on the fatigue strength of the joint; this is borne out by the data of Fig. 5.

It should be pointed out that these results were obtained with cyclic loading applied as a bending moment. Published data (Ref. 5) do not suggest that the same maximum fiber stresses applied at the weld toe by straight cyclic tension of the cantilever (instead of bending) would alter substantially the response of this region to fatigue. Tears more distant from the weld toe might be more damaging in tension than in bending. However, they still should be milder in effect than tears at the weld toe, since deeply buried flaws are known to be less harmful in impact and fatigue loading than flaws near the surface.

A second observation is that, in a service structure weld joint, tearing would likely be irregular and intermittent along the weld length. Thus, the extent of the lamellar tearing would have to be averaged over the weld length in order to gage its effect on fatigue resistance.

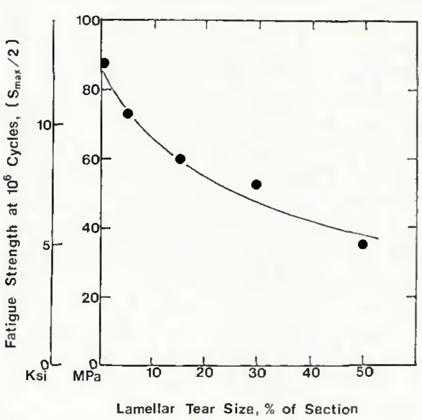

Fig. 7—Effect of lamellar tear size on fatigue strength

Joint Toughness

The toughness tests on the welded joints were conducted at several temperatures between 20 and 150°C (68 and 302°F)—Table 3. This is the temperature range in which the A572 steel exhibited a transition from cleavage to fibrous fracture. The complete test results are displayed in Figs. 8 and 9.

Figure 8 shows the energy absorbed by the test specimens as a function of the temperature and the percent tearing in the joint (circled numbers). The most noteworthy feature of these data is the low level of toughness exhibited by completely sound joints in a steel strongly susceptible to lamellar tearing. The maximum energy absorption was less than 12 joules/cm^2 (77J/in^2) in the fibrous fracture temperature range. Also, Charpy tests at 20°C (68°F) showed only 7 Joules when oriented with their lengths in the thru-thickness direction.

By contrast, a bend test on an A572 steel highly resistant to lamellar tearing showed an energy absorption of 54 joules/cm^2 (348J/in^2) and did not fracture at the maximum deflection possible in the test jig. The presence of lamellar tearing lowered the toughness even further, but the data showed an extensive scatter. Figure 9 indicates, however, that the load-carrying capacity of the joint as

Table 2—Fatigue Test Data

Specimen	Percent tear	Stress Range ($\frac{1}{2}S_{max}$) MPa	(ksi)	Cycles at first crack	Cycles at 10% load drop
Single-weld tests:					
1	0	132	(19.0)	8,000	54,000
2	0	126	(18.2)	48,000	144,000
3	0	117	(17.0)	60,000	200,000
4	0	112	(16.2)	–	193,000
5	0	102	(14.7)	250,000	730,000
6	0	97	(14.0)	325,000	760,000
7	0	93	(13.4)	200,000	350,000
8	0	87	(12.5)	277,000	1,017,000
9	0	83	(12.0)	>2,000,000	>2,000,000
10	6	122	(17.7)	150,000	368,000
11	55	97	(14.1)	245,000	560,000
12	60	83	(12.0)	625,000	1,730,000
13	75	78	(11.3)	60,000	72,000
14	75	69	(10.0)	550,000	567,000
15	80	97	(14.0)	31,000	32,000
Cut-and-reweld tests:					
16	1	87	(12.5)	–	325,000
17	2	93	(13.4)	–	1,250,000
18	2	80	(11.5)	1,900,000	2,217,000
19	2	69	(10.0)	>2,000,000	>2,000,000
20	5	78	(11.3)	–	503,000
21	10	69	(10.0)	–	1,090,000
22	15	73	(10.6)	–	260,000
23	15	63	(9.1)	250,000	441,000
24	20	69	(10.0)	–	620,000
25	25	59	(8.6)	–	1,385,000
26	33	52	(7.7)	–	715,000
27	50	56	(8.1)	5,000	31,000
28	60	59	(8.6)	–	28,000
29	65	34	(5.0)	–	572,000

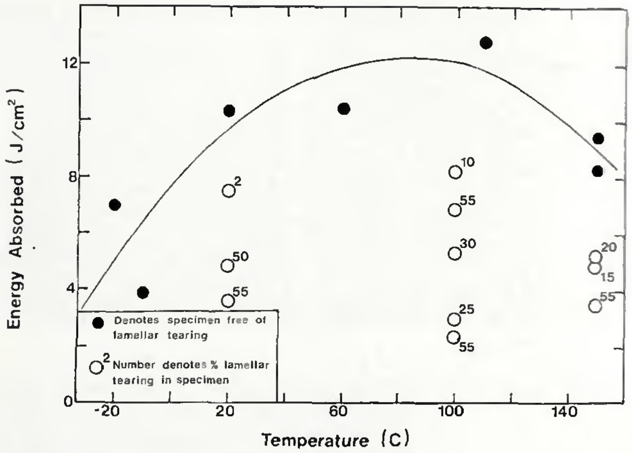

Fig. 8 — Effect of buried lamellar tears on the toughness of the welded T-joint

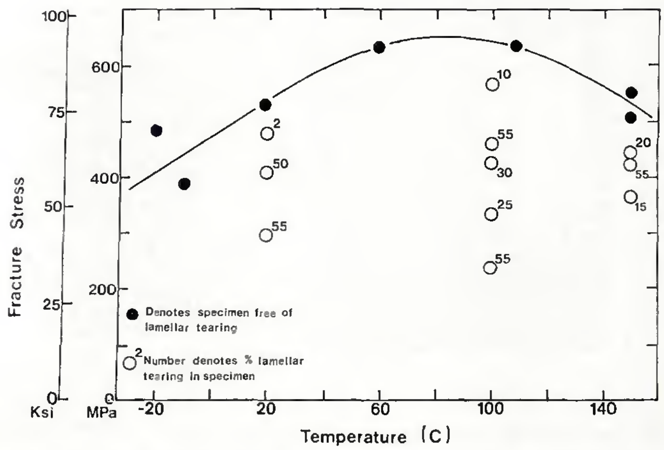

Fig. 9 — Effect of buried lamellar tears on the fracture stress of the welded T-joint

signaled by the maximum failure stress does not fall below one-third the steel tensile strength even with lamellar tearing levels of 25%. In a previous paper (Ref. 4), it was shown that tears located well away from the weld toe did not detract seriously from the bending strength of the joint.

In general T-joints in material that is markedly susceptible to lamellar tearing display low energy absorption under through thickness tension stresses whether tearing is actually present or not. Tearing will deteriorate toughness further, but the delamination produced by welding restraint probably makes the amount of continuous, measurable lamellar-tearing of secondary importance.

Metallurgical Examination

Buried Lamellar Tearing. The sections that were trimmed from the sides of the cantilever specimen were polished and lightly etched to determine the location and extent of the buried tears. Figure 10 illustrates the tears that were produced by the single weld technique and by the cut-and-rewelding technique, respectively.

It can readily be recognized that the tear close to the weld toe should exert a stronger effect on the fatigue resistance than the tear near the weld root as demonstrated in Figs. 5 and 6. Figures 11 and 12 show the fatigue crack path in the two cases. By watching the test joints during cycling it was possible to see that the fatigue crack originated at the weld toe and grew downward to the tear in specimens containing a tear that was remote from the toe. However, in tests containing the tear next to the weld toe, the fatigue crack grew upward from the tear until it surfaced in the adjacent weld metal. Further growth then proceeded downward from the bottom of the tear.

Table 3—Dynamic Fracture Test Data[a]

Specimen	Percent tear	Test temperature, °C[b]	Fracture stress MPa	(ksi)	Energy absorbed, Joules/cm²
1	0	−20	485	(69)	7.1
2	0	−10	390	(56)	3.9
3	0	20	525	(75)	10.3
4	0	60	635	(91)	10.5
5	0	110	635	(91)	12.9
6	0	150	545	(78)	9.5
7	0	150	510	(74)	8.2
8	2	20	485	(69)	7.5
9	50	20	410	(58)	4.8
10	55	20	295	(42)	3.7
11	10	100	570	(81)	8.2
12	25	100	330	(47)	3.1
13	30	100	425	(61)	5.4
14	55	100	240	(34)	2.3
15	55	100	465	(67)	6.8
16	15	150	365	(52)	4.9
17	20	150	425	(61)	5.2
18	55	150	425	(61)	3.7

(a) All specimens prepared by cut-and-reweld technique.

(b) $°F = \frac{9}{5}°C + 32$

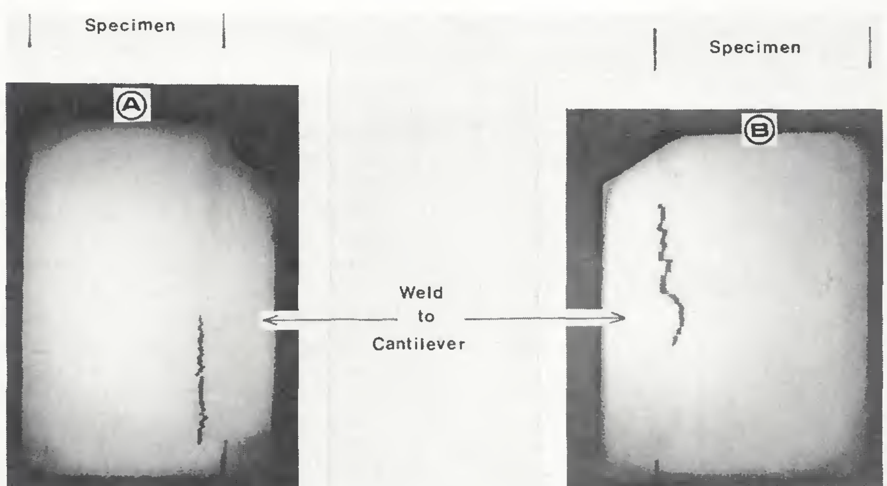

Fig. 10 — Comparison of buried tear locations obtained by the single weld and cut-and-reweld techniques: A — single weld technique; B — cut-and-reweld technique. X2 (reduced 41% on reproduction)

Fig. 11 — Path of fatigue crack from weld toe to tear remote from the toe. Nital etch; X2 (reduced 24% on reproduction)

Fig. 12 — Path of fatigue crack (fine dark line) from top of lamellar tear next to weld toe over to the toe. Nital etch; X2 (reduced 16% on reproduction)

SEM Fractography. Several of the fractures of specimens cycled to failure were examined by scanning electron microscopy (SEM) to learn whether there were distinguishing features between lamellar tears produced during welding and the fracture surface resulting from fatigue. These fractures revealed only subtle differences to the naked eye — Fig. 13.

As illustrated in Fig. 14, the lamellar tear shows a distinct pattern of void coalescence with numerous nonmetallics still in place; however, the fatigue fracture has a blurred appearance, probably produced by the cyclic rubbing of the opposing faces. The fracture produced by overloading to part the specimen from the cantilever shows a larger void size than the tear fracture, indicative of greater ductility at room temperature than at lamellar tearing temperatures where strain aging is believed to be operative.

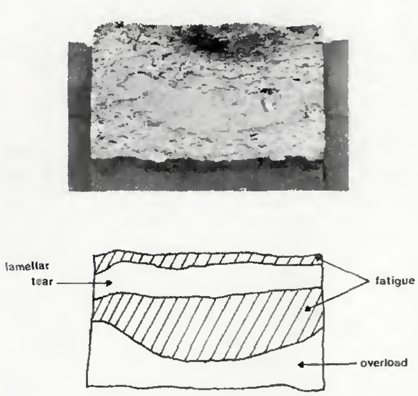

Fig. 13 — Fracture surface of a specimen containing a buried lamellar tear that was failed by fatigue and then broken apart. X1.5

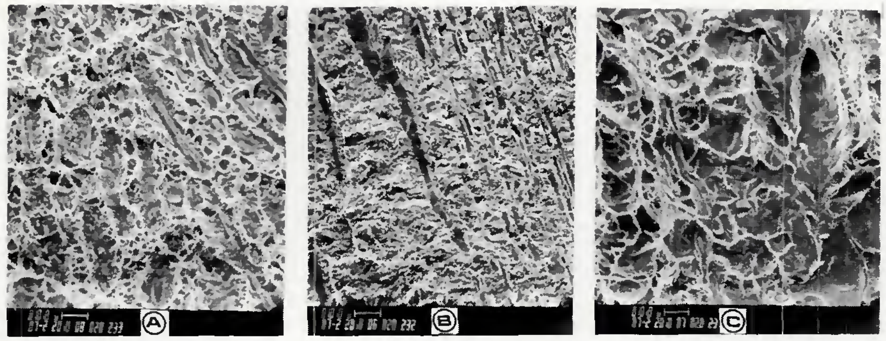

Fig. 14 — SEM photographs taken from three Fig. 13 areas: A — lamellar tear; B — fatigue fracture; C — overload fracture. X700 (reduced 54% on reproduction)

In a number of cases the fatigue fractures showed distinct striations similar to those observed by other investigators (Ref. 6). Figure 15 shows that these striations were sometimes tilted noticeably with respect to the fatigue crack growth direction, possibly in response to the details of the steel microstructure.

Summary

The results of the investigation may be summarized as follows:

1. Techniques were developed for producing partial lamellar tearing in a T-joint and for controlling the extent and location of the tearing with respect to the weld toe.

2. Under cyclic bending loads in one direction only (R = 0 at the weld toe), lamellar tears remote from the toe had relatively little influence on the fatigue resistance of the joint. By contrast, buried tears next to the weld toe had a larger effect in lowering fatigue resistance than the loss of load-supporting area they represented. Thus, a tear intersecting 5% of the weld area lowered the fatigue strength at 10^6 cycles by 17%. The fatigue strength levels of tear-free joints observed in this investigation are compatible with those in the published literature.

3. At elevated strain rates ($0.05\ s^{-1}$), a steel known to be highly sensitive to lamellar tearing exhibited low toughness in T-joints loaded in the thickness direction even in the absence of lamellar tearing. The presence of buried tears next to the weld toe lowered the energy to fracture further at testing temperatures covering the brittle fracture transition range of the steel.

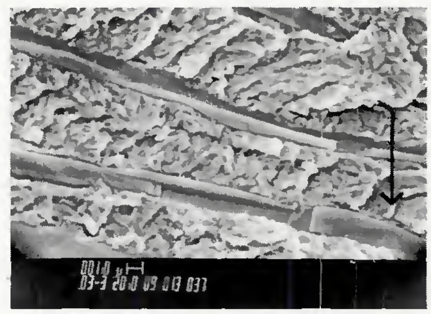

Fig. 15 — SEM photograph showing striations that developed in the fatigued specimen fracture; arrow indicates direction of macroscopic crack growth. X3,000 (reduced 37% on reproduction)

Acknowledgment

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The authors are solely responsible for the contents of this paper, and neither the sponsors nor any of their members warrant the accuracy of the data in the paper or any conclusions contained in it.

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