



A Quantitative Weldability Test for Susceptibility to Lamellar Tearing

Suitable for laboratory use, the test shows Al-Si killed steels to be less susceptible than Si killed steels

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ABSTRACT. An important aspect of current research on lamellar tearing is the development of a testing technique that will provide a quantitative assessment of material susceptibility. The majority of investigations have approached this problem in an indirect manner, attempting to correlate short transverse material properties to lamellar tearing susceptibility. This approach requires that the lamellar tearing resistance of the material already be known. Weldability tests are the most realistic technique for directly evaluating lamellar tearing susceptibility but they have been limited in the past by the cost of testing and the difficulties in quantifying and in interpreting the results. This report describes the development and evaluation of a quantitative weldability test (the Lehigh lamellar tearing test) to overcome these limitations.

Lamellar tears were generated with the Lehigh lamellar tearing test specimen in three of four materials investigated. These materials represented a wide range of lamellar tearing susceptibility. The test made it possible to measure a quantitative external restraint level required to produce a critical size lamellar tear. The magnitude of this external restraint

level proved to be consistent with information on the lamellar tearing susceptibility obtained from actual shop fabrication experience. The restraint required to cause lamellar tearing was correlated with selected aspects of the short transverse mechanical properties and the inclusion distribution in the material. The Lehigh test results were closely reproducible for the steels sensitive to lamellar tearing but were less consistent for a marginal steel for which loads well above the yield strength of the material were necessary to cause failure.

With the Lehigh test results as a measure of lamellar tearing susceptibility, the relationship between inclusion content and distribution, short transverse mechanical properties and lamellar tearing susceptibility were investigated. The results showed a clear correlation between the tension test elongation, the room temperature Charpy test energy and the lamellar tearing susceptibility only if these short transverse test values were obtained in the region of potential tearing, generally within $\frac{3}{8}$ inch distance from the weld. Predictions of tearing susceptibility are often unreliable when they are derived from the short transverse properties of regions at a greater depth in the plate thickness. Reduction in area measurements did not correlate very consistently with lamellar tearing susceptibility.

The results of this investigation also revealed differences in the mechanism of lamellar tearing in the Si killed steel versus the Al-Si killed steels. These differences were attributed to differences in inclusion type and to the brittle fracture transition temperature. The tests demonstrated that the lamellar tearing resistance of the Si killed steel could be improved 35% by preheating to above the brittle fracture transition temperature.

Introduction

Lamellar tearing is a form of cracking that occurs in the base metal of weldments due to the combined effects of the anisotropic characteristics of hot rolled steel plate and high stresses generated by weld thermal contraction acting perpendicular to the rolling plane. This cracking is usually associated with highly restrained Tee or corner joints where the weld fusion boundary is parallel to the rolling plane of the plate. The metallographic profile of a lamellar tear is characterized by terrace fracture surfaces parallel to the rolling plane of the plate joined in a step-like manner by shear wall fractures perpendicular to the rolling plane. The terrace fracture surfaces are shown to be associated with elongated or aligned inclusions, a material characteristic which also causes poor short transverse mechanical properties.

Lamellar tearing is not a new phe-

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nomenon. It has undoubtedly existed since the inception of fusion welding on large wrought steel structures. It was not until the demand for high integrity structures necessitated the use of more sophisticated nondestructive testing procedures that lamellar tears were identified. Today lamellar tearing is reported to be a problem in shipbuilding, atomic power plant construction, bridge construction, building construction, boiler fabrication and in the construction of chemical and nuclear pressure vessels, offshore drilling rigs and rail cars. The steel manufacturers and fabricators are concerned about lamellar tearing for reasons such as the following:

1. The tearing can destroy the integrity of the joint.
2. Unless ultrasonic examination is carried out, lamellar tears are very difficult to detect and may go undetected until a service failure occurs.
3. The repair procedures for lamellar tearing are difficult, costly, usually time consuming and occasionally impracticable.
4. There is currently no generally acceptable procedure for assessing material susceptibility to lamellar tearing.

The development of a quantitative test for accurately measuring lamellar tearing susceptibility is therefore an important aspect of current lamellar tearing research.

Investigators have addressed this problem indirectly by comparing the service history of the plate with such parameters as the short transverse mechanical properties, the ultrasonic attenuation properties or the inclusion content and distribution of the plate. The effectiveness of these parameters as useful quantitative measures of lamellar tearing susceptibility is limited experimentally by the lack of a direct quantitative measure of lamellar tearing susceptibility to verify these indirect correlations and conceptually by their failure to simulate testing conditions common to lamellar tearing service applications.

Weldability testing as a direct measure of lamellar tearing susceptibility is appealing because this type of testing may be designed to closely simulate actual service conditions. The effects of welding variables, material variables and restraint variables can all be studied with this type of testing. Several researchers have

been successful in creating lamellar tears in the research laboratory (Refs. 8, 11, 23, 26). Unfortunately the quantitative measures of lamellar tearing susceptibility have been difficult to interpret and reproduce and the testing procedures have been expensive.

The purpose of this paper is to describe the development and effective use of a new lamellar tearing weldability test for quantitatively measuring susceptibility to lamellar tearing.

Experimental Procedure

Development of Weldability Test Procedure

The design criteria for a quantitative lamellar tearing weldability test are defined by production requirements. These criteria include the following:

1. The test must be versatile enough to produce lamellar tearing over a range of materials, welding conditions, and restraint severity.
2. The test results must be easy to interpret.
3. The test results must be reproducible within the limits established by variations in the characteristics of the steel.
4. The test must be economical to perform and analyze.

Lamellar tearing may occur under two conditions of loading. The first (called rotation type lamellar tearing in this paper) occurs when the members being welded are free to rotate. The Cranfield specimen produces rotation-type lamellar tearing. The second type of lamellar tearing (called pull-type lamellar tearing in this paper) occurs when the members being welded are restrained from rotating. Crack initiation usually occurs below the plate surface and is seldom associated with the root of the weld. Numerous attempts have been made to produce pull-type tears in laboratory size specimens economically. The results show that massive structural restraint is required if adequate short transverse plastic strains are to be produced by weld contraction alone. Since this restraint is troublesome to create and difficult to analyze quantitatively, a more convenient means of generating short transverse strain (to be used to supplement weld thermal strain) was sought. The Lehigh lamellar tearing test uses an external load applied during welding for this purpose.

A welding fixture (Fig. 1) was constructed to permit the deposition of a single-bevel groove weld between the test specimen and a cantilever beam under variable degrees of external restraint provided by external hydraulic loading. The setup is schemat-

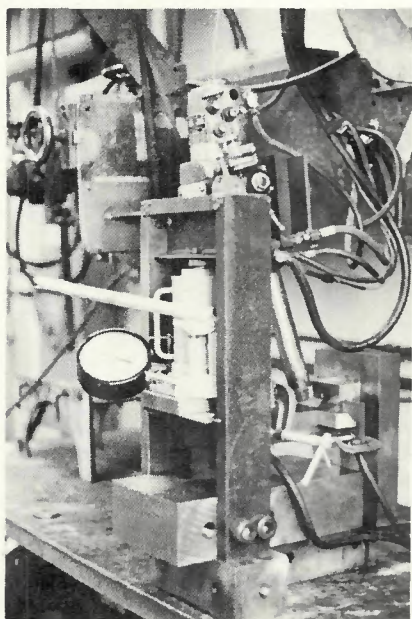


Fig. 1 — The fixture and welding facility for the Lehigh lamellar tearing test

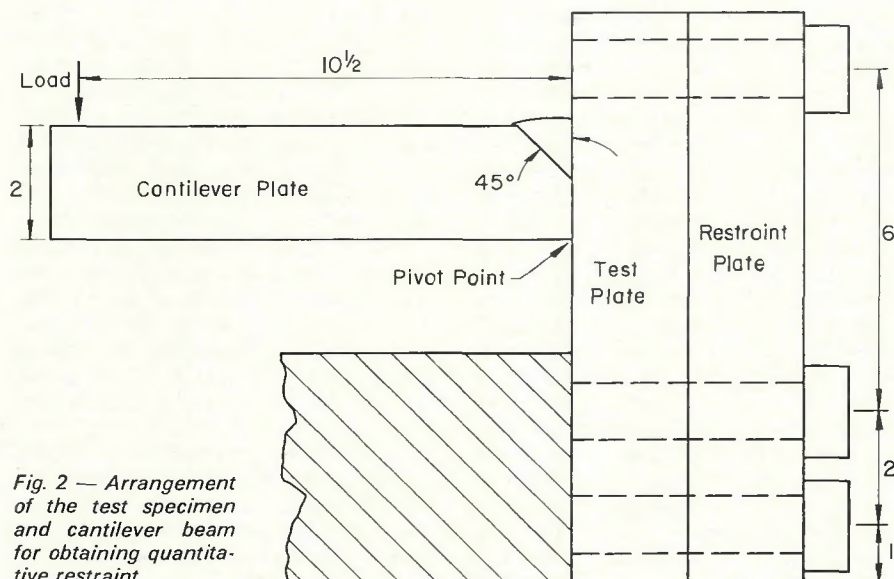


Fig. 2 — Arrangement of the test specimen and cantilever beam for obtaining quantitative restraint

ically shown in Fig. 2. A bending load applied to the cantilever beam provided a controllable amount of applied through-thickness stress in the test plate. Since this external load could be applied at any time in the welding sequence and since it could be maintained for any portion or all of the welding process, the technique offered versatile testing conditions for studying lamellar tearing mechanisms.

The test design incorporated the following features:

1. The cantilever beam dimensions were standardized for all material compositions and section thicknesses to be tested. It is 3 in. wide × 2 in. deep × 10.5 in. long (or greater) and made from a steel greater in strength than the test plate.
2. The filler metal used to produce the groove weld between the test plate and the cantilever beam was a low alloy steel depositing metal of higher strength than the steels tested.
3. The test plate was restrained from bending by a backing plate shown in Fig. 2. The amount of external restraint required depended on the thickness and yield strength of the test plate. It was the objective to eliminate yielding of the test plate in bending as a limiting factor to the loading level attainable.
4. The cantilever beam was designed with a pivot point 1 to 1½ in. below the weld. Since the pivot point carried the compressive stresses of bending, it created a general state of tension across the entire welded joint. That tension was imposed on the entire weld area was verified by the observation of inclusion separations all along the weld height.
5. During successive welding passes the amount of external load applied was increased proportionately to the increase of cross sectional area of the test weld carrying the load, thus maintaining the unit stress on the weld constant.

The following sequence of procedures was followed during the preparation and testing of a Lehigh lamellar tearing specimen:

1. The test plate was machined to the dimensions illustrated in Fig. 3. All oxides were removed from the plate surfaces by machine grinding.
2. The cantilever plate was cut several inches longer than required so that it could be used for several test specimens. The 45 deg bevel was cut with a band saw. No precision machining was required.
3. The test and cantilever plates

Table 1 — Chemical Composition of Test Steels

Element	A515-70 heat G	A516-70 heat E	Mil-16113C heat J	Mil-24113C heat L
C	.30	.24	.19	.23
Mn	.83	1.19	.97	1.21
P	.005	.01	.007	.007
S	.029	.021	.02	.02
Si	.23	.25	.23	.24
Ni	.07	.10	.10	.15
Cr	.03	.07	.08	.10
Mo	.02	.02	.02	.023
Cu	.075	.14	.14	.19
V	.002	.004	.045	.004
Al	.005	.054	.033	.043
Sn	.003	.005	.008	.01
Ti	.005	.005	.013	.006
N	.007	.0075	.0077	.0079
O	.014	.0033	.0022	.0026
Plate thick- ness, in.	2½	1	2	2

were joined at the pivot point (Fig. 2) with small tack welds by the manual shielded metal-arc process and ⅛ in. E7014 electrodes. Two-inch-long start and stop tabs were also tack welded to the test specimen.

4. The specimen was thoroughly cleaned with acetone to remove all oil and grease.
5. The distance from the bottom of the groove to the top of the cantilever plate (d_o in Fig. 4) was measured.
6. At the completion of each weld layer the distance from the top of that layer to the top of the cantilever plate was measured (d_i , where i refers to the layer measured).
7. The load in pounds required for the desired weld restraint level (WRL) (in psi) was then calculated for each layer of welding from the following formula:

$$P = \frac{(WRL)B(d_o - d_i) \left[(t - d_o) + \frac{d_o - d_i}{2} \right]}{D}$$

P = load applied to the cantilever plate

D = distance from the loading point to the surface of the test specimen

B = width of the test specimen

d_o = distance from the bottom of the groove (before welding) to the top of the cantilever plate

d_i = distance from the top of the i -th weld layer to the top of the cantilever plate

t = thickness of the cantilever plate

This load was applied when the weld metal had cooled to a temperature of 200 F.

8. During each weld deposit the re-

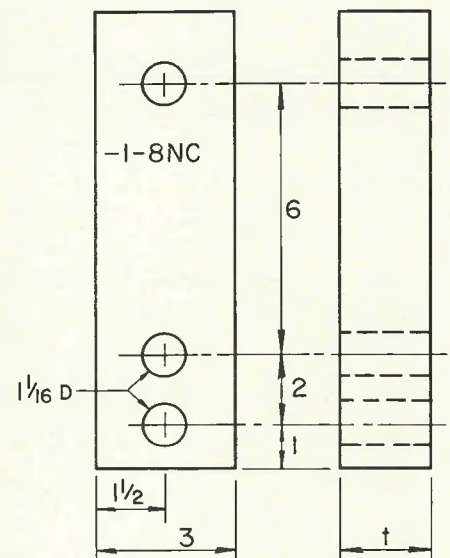


Fig. 3 — Dimensions of the test specimen

straining load dropped because of high temperature yielding. The hydraulic jack was not adjusted during this period. The load was restored to its appropriate value when the weld metal temperature had dropped to 200 F.

9. The weld metal was deposited in layers as illustrated in Fig. 4. At the completion of each weld layer the load was adjusted to the requirements of the desired weld restraint level. The weld passes made prior to the completion of a weld layer were deposited at a load level appropriate for the previously completed layer.

Materials

The materials used in this investigation are listed in Table 1. These

plates were selected for the weldability test because they were supplied by fabricators who had experience with their behavior in shop construction. All the plates were tested in the normalized condition. The A515-70 plate was a 2½ in. thick Si killed steel which exhibited extensive lamellar tearing during the fabrication of a large gas turbine housing. The three remaining plates were Al-Si killed fine grained steels. The A516-70 steel was a 1 in. thick plate contemplated by the fabricator as a replacement for the A515-70. The MIL-S-16113C Type 2 was a 2 in. thick Mn-Ti-V ship steel reported to have a long history of lamellar tearing. The MIL-S-24113C Type 2 was a 2 in. thick C-Mn ship steel chosen by ship builders as a replacement for MIL-S-16113C.

Welding Procedure

The welding was performed with the gas metal-arc process on the

welding fixture shown in Fig. 1. All weld passes were deposited at a weld heat input of 40,000 joules/inch with dc reverse polarity, 325 A, 25 V, and a travel speed of 12.5/ipm. The shielding gas was argon-2% O₂ at a flow rate of 50 cfh, and the electrode was 1/16 in. diam low alloy steel barewire.

Results and Discussion

Because of its history of lamellar tearing fabrication failures, the A515-70 Si killed steel was selected for determining the feasibility of creating pull-type lamellar tears and measuring lamellar tearing sensitivity with the Lehigh lamellar tearing test. Five specimens (Nos. 1 thru 5) were tested under the loading conditions described in Table 2 to determine the feasibility of quantitatively evaluating lamellar tearing sensitivity in terms of a controlled critical restraint level (applied during welding) that will

create a lamellar tear of sufficient length (Fig. 5) to initiate rapid fracture either upon completing the welding passes or upon application of a slight overload after welding (Fig. 6).

The critical restraint level for A515-70 was determined to be 44 ksi. Welding with an applied restraint above the critical level (Specimen 5) resulted in fracture during the welding sequence. Welding with an external restraint less than the critical level resulted in some tearing damage but it always produced a weldment more resistant to overloads after welding than those weldments fabricated at the critical restraint level. Specimen 4 (which was welded without external restraint) showed no microstructural or ultrasonic evidence of mechanical damage after overloading to 60 ksi of restraint.

A second series of tests (Specimens 6 thru 9) was conducted to study the characteristics of the lamel-

Table 2 — Weldability Test Results

Steel	Specimen number	WRL, ksi	Visual	Evidence of failure			Postweld reload to rupture, ksi	Remarks
				Ultra-sonic	Metallo-graphic			
A515-70	1	44	Yes	Yes	Yes		44.5	This was the critical WRL.
A515-70	2	38	No	Yes	Yes		—	Metallographic evidence was very limited.
A515-70	3	38	No	Yes	Yes		53	
A515-70	4	0	No	No	No		(60)	No rupture produced at 60 ksi.
A515-70	5	52.5	Yes	Yes	Yes		—	Failure occurred 2/3 of the way through the 6th weld pass.
A515-70	6	44	No	Yes	Yes		—	Verifies extensive subcritical lamellar tearing at the critical restraint level.
A515-70	7	44	No	Yes	No		—	Ultrasonic indications were evident only while the specimen was loaded.
A515-70	8	44	No	Yes	Yes		—	Ultrasonic indications were evident after load removal.
A515-70	9	42	No	Yes	Yes		—	Large ultrasonic indications after load removal.
A515-70	10	50	No	Yes	Yes		—	Crack front detected. Specimen welded with 200 F preheat.
A515-70	11	55	No	Yes	Yes		68	Specimen welded with 200 F preheat.
A516-70	12	51	No	No	No		—	
A516-70	13	53	Yes	Yes	Yes		48.5	Pullout occurred during loading prior to the 7th weld pass.
A516-70	14	48.6	No	No	No		—	
A516-70	15	0	—	—	—		57.3	
A516-70	16	40	—	—	—		55.5	
A516-70	17	47.5	—	—	—		52.5	
Mil-S-16113C	18	60	No	Yes	Yes		—	A small lamellar tear was located outside heat affected zone.
Mil-S-16113C	19	75	Yes	Yes	Yes		—	Lamellar tear occurred in heat affected zone after 8th weld pass.
Mil-S-16113C	20	70	No	No	No		—	
Mil-S-16113C	21	75	No	Yes	No		—	
Mil-S-24113C	22	75	No	No	No		—	Weld metal failure initiated at lack of fusion.
Mil-S-24113C	23	50	No	No	No		94	

lar tearing during the early stages of initiation and propagation with the hope of identifying the significant aspects of the microstructure affecting lamellar tearing sensitivity. The tearing process was monitored ultrasonically between weld passes so that the test could be interrupted at a predetermined time. The specimens were then sectioned and metallographically examined to determine the type, location and distribution of the inclusions initiating lamellar tearing.

Several important observations were made concerning the inclusion separation observed in these four specimens.

1. Ultrasonic indications of inclusion separations observed in a highly restrained specimen during loading usually diminished in intensity and sometimes disappeared when the external restraint was removed. This effect was probably associated with closing of the openings along inclusions when elastic recovery restored the shape of the test specimen. If tearing was in the early stages of initiation and propagation, metallographic evidence of damage was often impractical to locate.
2. The first metallographic evidence of lamellar tearing was the terrace linkage of inclusions in close proximity to each other (at arrow in Fig. 7). The propensity for this linkage depended upon the length of the inclusions (or groups of inclusions which had already linked), the distance between them, and their position in the plate. This inclusion linkage did not appear to be associated with a definite crack front. Instead it was randomly dispersed.
3. In all specimens of the A515-70 steel examined, the inclusions participating in the initial inclusion linkage were complex Al-Mn-silicate stringers (see Fig. 8). No evidence of MnS-initiated tears was detected. In fact, MnS stringers adjacent to the crack front were observed not to crack (Fig. 9). Once inclusion linkage in a localized region became extensive, a main crack front formed. This crack front often had regions of multiple crack propagation. As many as four parallel cracks were observed in the same crack front. As to be expected some of these cracks were unassociated with inclusions that are visible on the plane of polish.

Characterization of the Fracture Surface

A scanning electron microscope examination of the lamellar tears in

A515-70 showed the fracture mechanism on the terrace surface to be a combination of decohesion at the inclusion-steel interface (Fig. 10a), dimple rupture (Fig. 10b) and quasi-cleavage (Fig. 10c). Also common to the fracture surface were high ridges similar to the ridge shown in Fig. 10c and more clearly in Fig. 10d.

The regions of quasi-cleavage and the distinct ridges on the fracture surface were found only in the A515-70 steel. Ridges can form by the joining of two elliptical shaped crack fronts which are propagating toward each other. If this is true, these ridges offer fractographic evidence for the observation that inclusions separate from the metal in many locations and later extend and join to form a main crack front. The explanation for the regions of quasi-cleavage is a little more subtle.

Early metallographic evidence for lamellar tearing in A515-70 was in the form of inclusion linkage (Fig. 7). The metallic region between these inclusions (which act as notches) is highly restrained by the surrounding matrix. On a localized perspective this is analogous to a double notch tensile specimen. This matrix restraint creates a high triaxial stress state in the region between the inclusions. The degree of triaxiality depends upon the length of the inclusions (l_i) and the distance between them. When $(l_1 + l_2)/d$ is large, the triaxiality is large and the inclusions will link in a brittle manner by quasi-cleavage if the process takes place below the transition temperature of the steel. For lower $(l_1 + l_2)/d$ conditions the metal may break in a less brittle manner by dimple formation. This theory would therefore allow the existence of both fracture characteristics on the same fracture surface.

Effects of Preheat

If the quasi-cleavage formed during tearing indicates a reduced resistance to tear propagation, the resistance to lamellar tearing should improve by raising the weld interpass temperature above the transition temperature. To test the premise, two Lehigh lamellar tearing tests (Specimens 10 & 11) were conducted on A515-70 with a 200 F preheat and interpass temperature. The results are listed in Table 2. A shortage of material prevented additional testing. The estimated critical restraint level of 60 ksi is believed, however, to be within a few ksi of the actual value. This estimated value represents a 35% improvement in resistance to lamellar tearing by the use of a relatively low preheat temperature.

Two reasons for this improvement can be postulated. The first is the re-

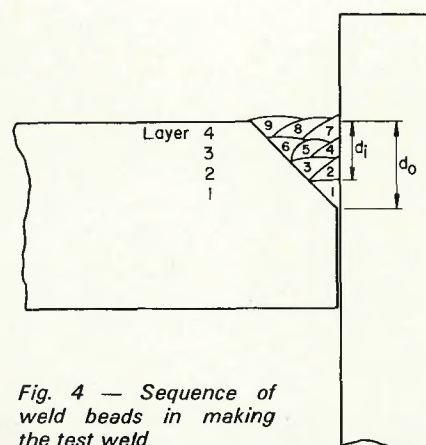


Fig. 4 — Sequence of weld beads in making the test weld



Fig. 5 — Lamellar tear produced during welding sequence in A515-70 steel loaded to 44 ksi

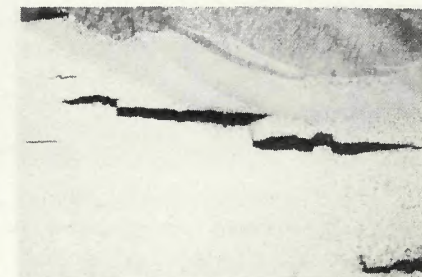


Fig. 6 — Lamellar tearing produced by postweld loading of A515-70 steel

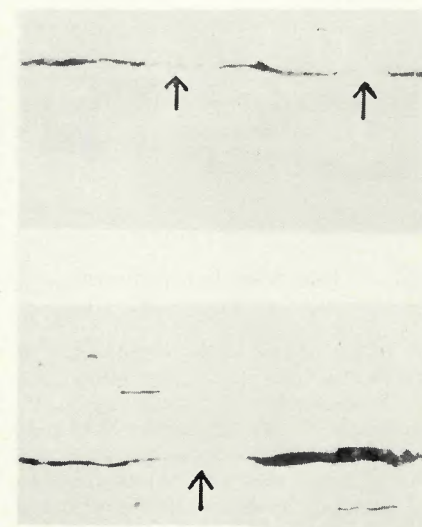


Fig. 7 — Examples of terrace linkage of inclusions in close proximity and in the same plane

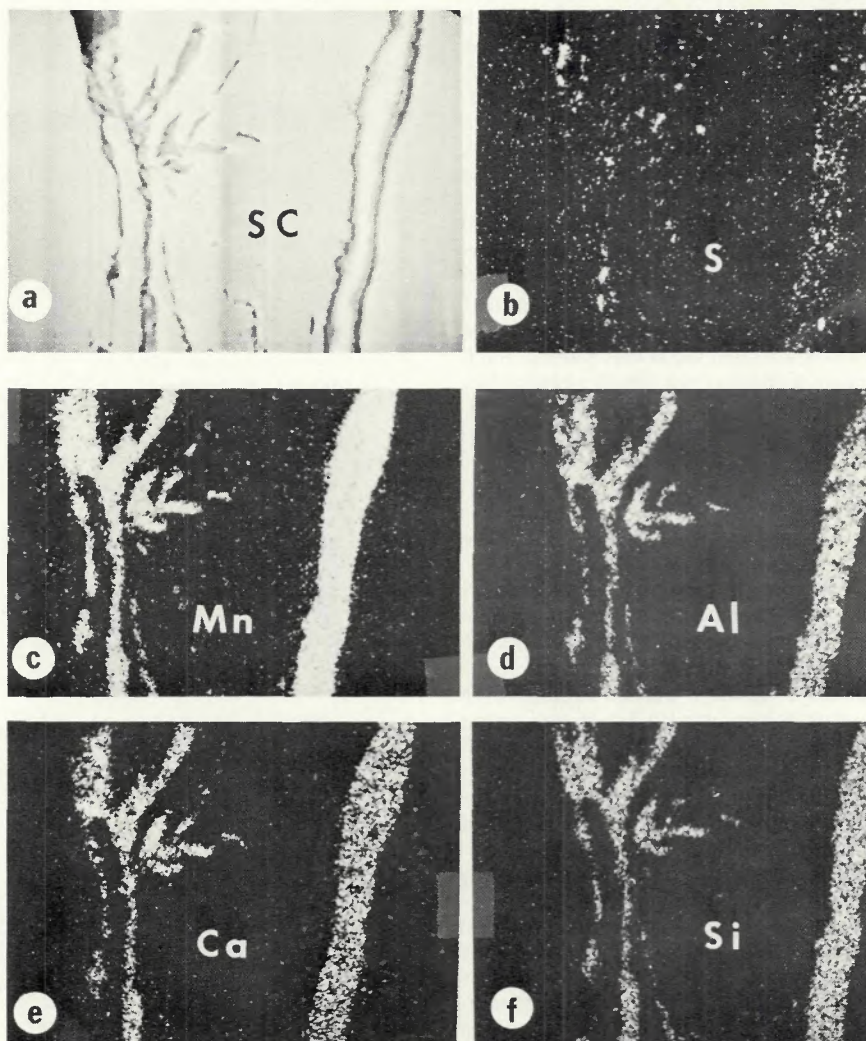


Fig. 8 — Identification of inclusion in early lamellar tear by microprobe analysis. (a) sample current, (b) sulfur scan, (c) manganese scan, (d) aluminum scan, (e) calcium scan, (f) silicon scan



Fig. 9 — View of tear region involving silicate inclusions but with sulfide inclusions intact

tardation of the early propagation of lamellar tearing by reducing the tendency for brittle fracture by quasi-cleavage. A fractographic examination of the fracture surface in Specimen 11 revealed a complete absence of quasi-cleavage on the preheated specimen (Fig. 11). The second possible reason is the reduction of plastic strains in the vicinity of the weld by a reduction in the weld thermal gra-

dients. The predominant reason is difficult to determine.

In an attempt to evaluate the importance of the reduction in the weld thermal gradients, a Lehigh lamellar tearing test was performed on the A516-70 material preheated to 200 F. Since the room temperature tests on this material did not exhibit quasi-cleavage fracture, the influence of this factor was eliminated. A 6%

improvement in the lamellar tearing resistance of A516-70 was therefore attributed to the reduction in plastic strains associated with a 200 F pre-heat. Since this percentage is far less than the 35% improvement measured for A515-70, the elimination of quasi-cleavage in the silicon killed steel was deemed highly significant.

Short Transverse Properties of A515-70

Both the Lehigh lamellar tearing test results and prior fabrication experience showed that the heat of A515-70 plate was very susceptible to lamellar tearing. The short-transverse tensile properties for this material are listed in Table 3. The most significant feature of these properties was the marked difference in the reduction of area properties observed in the center region of the plate as compared with those in the near surface region. The test gage lengths of the first four specimens listed in Table 3 were centered on the midthickness of the plate. The reduction in area values obtained for all four specimens were acceptably high for material expected to resist lamellar tearing.

The next four short-transverse tensile specimens were centered at a point $\frac{1}{4}$ in. below the plate surface. The location of fracture in these specimens was consistently $\frac{3}{16}$ to $\frac{1}{4}$ in. from the weld fusion line in a region just beyond the visible heat affected zone. The reductions in area exhibited by near-surface metal were a small fraction of those measured in the first four specimens, and they were in accordance with the poor lamellar tearing resistance exhibited by this heat of A515-70 steel.

The reduction in area was not the only short-transverse property exhibiting large variations with respect to the position in the plate. The energy absorptions of room temperature Charpy V-notch short-transverse specimens with the notch located $\frac{1}{4}$ in. from the surface of the plate were only $\frac{1}{5}$ as great as those for specimens with notches located at the mid-thickness (Table IV), and the average tensile strength was 22.4 ksi lower near the plate surface than at the plate midthickness. It is important to note that the position of fracture had no significant effect on the yield strength of the material.

Strain Aging Tests

Thermal strain aging produced by welding was thought to be a possible explanation for the large variations in short-transverse properties. Since this behavior was observed only in the A515-70 steel and since A515-70 is the only silicon killed steel (the aluminum in the Al-Si killed steels ties up the nitrogen and reduces

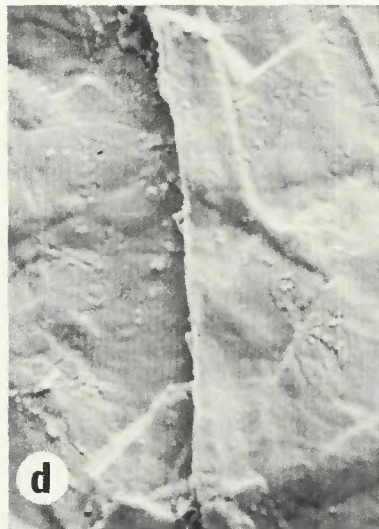
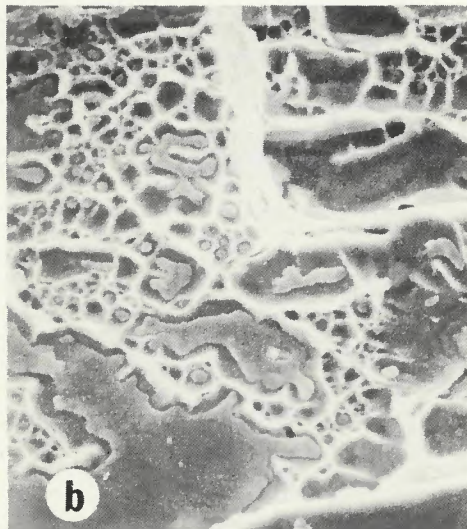
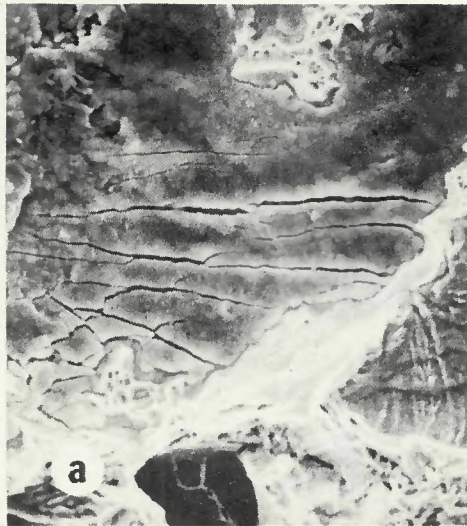


Fig. 10 — Fracture mechanisms in the lamellar tearing of A515-70 steel. (a) decohesion and cracking of inclusions (X1000, reduced 14%); (b) dimple rupture area in tear (X2000, reduced 14%); (c) quasi-cleavage area in tear (X500, reduced 14%); (d) ridge area in tear (X500, reduced 14%)

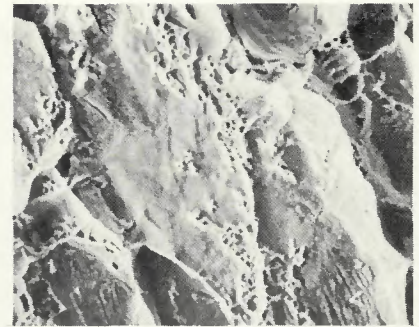


Fig. 11 — Fracture surface of lamellar tear in A515-70 steel preheated to 200 F (X400, reduced 32%)

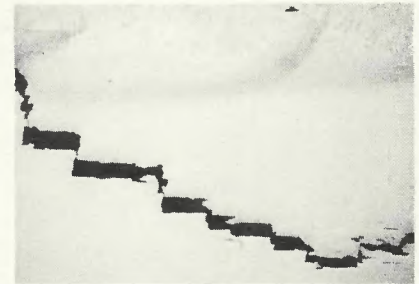


Fig. 12 — Fracture profile of lamellar tearing in A516-70 steel

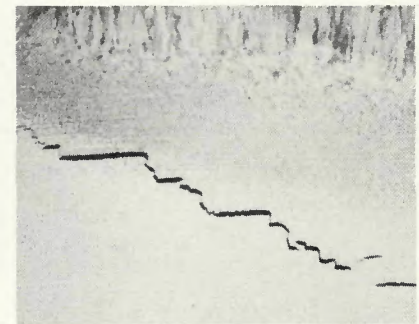


Fig. 13 — Lamellar tearing profile in Mil-S-16113C steel

strain age sensitivity), this premise was worthy of further consideration. Short-transverse tests were run to determine if the centerline values of reduction in area would be reduced by strain aging to the value observed in metal near the surface after welding. Longitudinal specimens were used to compare the strain age sensitivity of the different materials. The results of these tests are presented in Table 5.

These data show that A515-70 was more strain-age sensitive than the Al-Si killed steels. This strain aging was always accompanied by a large increase in yield strength, which was due mainly to work hardening and partly to strain-age hardening. For the strain aging tests with the through-thickness specimens from the center of the plate, the yield strength increased 34 ksi due to work hardening and aging while the reduc-

tion of area decreased from 19 to 14%. In contrast, the short-transverse reduction in area near the edge of the welded plate was 2.8% compared to the 19% at the centerline, but there was no appreciable increase in the yield strength. This comparison indicates that strain aging is not responsible for the low ductility of the metal near the surface.

Inclusion Characteristics

Several other material variables may have affected the short-transverse properties near the surface of the A515-70 plate. An excessively high concentration of inclusions near the plate surface could account for the low properties, but quantitative metallography does not indicate either an excessive percentage of inclusions or an excessive amount of inclusion alignment and grouping. A

large difference in thermal expansion characteristics between the silicate inclusions and the steel matrix could result in material damage by the formation of microvoids near the weld. More work on steels exhibiting this short-transverse behavior is required before an explanation is forthcoming.

Sensitivity of the Lehigh Lamellar Tearing Test

Three additional steels were evaluated with the Lehigh lamellar tearing test to determine the response of the test to a range of lamellar tearing resistant materials. The results of these tests are listed in Table 2. A critical restraint level of 52,000 psi measured for the A516-70 plate proved to be consistent and reproducible. Tearing was not so consistent in the less susceptible MIL-S-

Table 3 — Through-thickness Tensile Properties (1/4 in. diam, 1 in. gage length)

Steel	Distance of fracture from fusion line, in.	Tens. str., ksi	Yield str., ksi	Red. area, %	Elong., %
A515-70	3/8	76.8	39.5	18.5	14.8
A515-70	1	77.0	39.0	23.4	20.2
A515-70	1/2	78.3	39.6	17.9	—
A515-70	3/8	76.2	39.1	17.3	15.2
A515-70	3/16	50.8	41.7	3.9	3.6
A515-70	1/4	47.0	39.7	1.3	2.0
A515-70	3/16	58.9	39.7	3.5	3.6
A515-70	3/16	62.1	49.2	2.5	—
A516-70	1/2	65.6	40.2	10.1	6.9
A516-70	1/2	65.6	40.4	10.2	8.2
A516-70	1/2	68.2	41.4	11.6	6.5
A516-70	1/2	68.8	41.0	11.0	6.7
Mil-S-16113C	9/16	58.0	42.2	8.3	—
Mil-S-16113C	11/16	63.2	43.7	11.0	—
Mil-S-16113C	7/8	59.2	43.0	12.6	—
Mil-S-16113C	3/4	65.7	44.2	10.5	15.5
Mil-S-16113C	3/4	62.1	42.6	14.7	17.5
Mil-S-24113C	1	73.5	48.7	24.0	17.9
Mil-S-24113C	1	76.7	49.1	24.2	21.6
Mil-S-24113C	1	75.2	45.7	25.4	20.7
Mil-S-24113C	3/4	77.2	46.2	17.7	18.2
Mil-S-24113C	11/16	79.2	47.6	20.7	—
Mil-S-24113C	11/16	77.2	47.3	22.2	19.8
Mil-S-24113C	3/4	78.3	49.3	23.2	—
Mil-S-24113C	5/8	78.8	49.1	22.8	—

Table 4 — Average Mechanical Properties of Test Steels

Steel	Direction ^(a) of test	Yield str., ksi	Tens. str., ksi	Red. area, %	Elong., %	Rm temp CVN, ft-lb
A515-70	Short Transv (m)	39.3	77.1	19.4	16.7	14.3
2 1/2 in thick	Short Transv (s)	42.6	54.7	2.8	3.1	3.5
Code G	Longitudinal	42.3	76.9	53.7	31.9	28.0
WRL=44 ksi	Transverse	39.7	77.8	54.8	30.6	18.0
A516-70	Short Transv (m)	40.8	67.1	10.6	7.1	8.4
1 in. thick	Short Transv (s)	—	—	—	—	15.0
Code E	Longitudinal	40.0	73.1	58.8	30.9	47.8
WRL=52 ksi	Transverse	41.8	73.0	56.9	30.4	35.3
Mil-S-16113C	Short Transv (m)	43.1	61.6	11.4	16.5	19.0
2 in. thick	Short Transv (s)	—	—	—	—	20.0
Code J	Longitudinal	50.0	70.1	62.7	33.5	102
WRL=75 ksi	Transverse	42.7	69.0	70.8	37.2	52.5
Mil-S-24113C	Short Transv (m)	47.8	77.1	22.5	19.5	23.4
2 in. thick	Short Transv (s)	—	—	—	—	26.7
Code L	Longitudinal	58.4	81.0	61.8	33.6	112
	Transverse	53.8	77.9	71.0	30.9	58.5

(a) m = midthickness, s = near-surface

16113C material (critical restraint level of 75,000 psi). These erratic results may have been due to the sensitivity of test to fluctuations in the inclusion distribution of a steel that is marginally susceptible to lamellar tearing. The MIL-S-24113C plate proved to be highly resistant to lamel-

lar tearing (see Table 2). The critical restraint level was not attained with the prototype test fixture.

Description of Lamellar Tears in the Al-Si Killed Steels

The fracture profiles of lamellar tears in A516-70 (Fig. 12) and MIL-S-

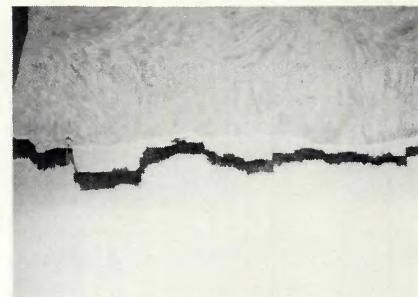


Fig. 14 — Lamellar tear in Mil-S-16113C

16113C (Figs. 13 and 14) differed from those of the A515-70 steel in several respects. The lamellar tears in the Al-Si killed steels were characterized by relatively small terrace fractures extensively joined by shear wall fractures. In contrast to A515-70, the terrace portions of the fracture did not appear to form independently of the vertical shear fractures. Instead the tears appeared to initiate in one location and propagate in a step-like manner from one terrace region to the next. Microprobe analysis of the inclusions in the uncracked matrix and scanning electron microscope analysis of the inclusions in the uncracked matrix and of the inclusions on the fracture surface enabled identification of two main types of inclusions responsible for tearing in the Al-Si killed materials. The long stringers were MnS inclusions of the type shown in Fig. 15. Silicate stringers were not found. Another type of inclusion in these steels was aluminum oxide (Fig. 15). These inclusions were small, jagged and often aligned to form rows of closely spaced inclusions.

The SEM fractographs of the lamellar tear produced in Specimen 13 (A516-70) are shown in Fig. 16. The terrace fracture surfaces were characterized by regions of inclusion decoherence and by regions of dimple rupture. In contrast with the A515-70 material, the terrace surfaces showed no evidence of quasi-cleavage (Fig. 16a). The visible inclusions on the fracture surface were identified as MnS stringers (Fig. 16b) and globular aluminum oxide particles (Fig. 16c). In comparison with the room temperature A515-70 lamellar tears, the A516-70 fracture surfaces had more shear wall fracture, a larger inclusion length to width ratio and more evidence of ductile fracture.

Indirect Testing Methods for Measuring Lamellar Tearing Susceptibility

The data from the Al-Si deoxidized steels in conjunction with that of the A515-70 material provide enough ex-

perimental data to establish general trends between short-transverse mechanical properties and lamellar tearing susceptibility. These results are plotted in Fig. 17. The most surprising aspect of these data is the lack of an apparent correlation between short-transverse reduction of area and the weld restraint level required to produce lamellar tearing. A strong correlation was exhibited between short transverse elongation and the lamellar tearing resistance but this property was extremely difficult to measure experimentally. This difficulty arose from frequent fracture outside the gage markings, poor fit-up after fracture, and secondary cracking away from the main crack front.

The best correlation of tearing sensitivity with an easily measurable short-transverse property was obtained with the room temperature Charpy V-notch tests. It should be noted that the Charpy energy levels varied considerably with the position of the notch in both A515-70 and A516-70 materials. In the A515-70 plate the energy absorption of metal near the surface was 15% that of metal near the midthickness. These variations were significant and the correlation with the weld restraint level was acceptable only when the lower of the two values were used. For the A515-70 plate, emphasis on the near surface properties was reasonable since this is the region in the plate where lamellar tearing occurred. Use of the midthickness properties in the A516-70 can be justified by the fact that it was a relatively thin plate and that the Lehigh lamellar tearing test produced tears at a depth only 1/8 in. from the midthickness. The observed correlation between room temperature short-transverse Charpy V-notch properties and the weld restraint level is worthy of further study.

One side observation from Fig. 17 concerns the weld restraint level required to produce tearing in MIL-S-24113C. Extrapolation of both the

elongation and the Charpy V-notch lines predicts the same weld restraint level for tearing in MIL-S-24113C (86 ksi). This restraint could not be obtained with the prototype testing fixture.

Inclusion Characterization

Extensive data from quantitative lineal analysis of the inclusion content and distribution for the four test steels are summarized in Table 6. When these inclusion counts are compared to Charpy energy values as in Fig. 18, it is notable that in the Al killed steels there is a progressive loss of toughness with higher inclusion count. The Si killed A515-70 steel is less tough for equivalent inclusion content. Previous discussion points to two possible reasons for this:

1. the high transition temperature of the A515-70 material
2. the predominance of silicate stringers unique to the A515-70 material.

A515-70 and MIL-S-16113C had similar inclusion contents and distributions. They differed however, in inclusion type and transition temperature. When the A515-70 was welded at a 200 F preheat temperature, the critical restraint level was raised from 44 ksi at room temperature to an estimated value of 60 ksi. If this improvement is assumed to be the result of eliminating quasi-cleavage fracture by testing above the transition temperature, a remaining difference between the preheated A515-70 material and the room temperature MIL-S-16113C was the type of inclusions in the steel. The critical restraint level for MIL-S-16113C was 75 ksi or more. The 15 ksi difference in critical restraint level between the steels may be attributed at least in part to the type of inclusions. These results indicated that the silicate inclusions as well as the coarse grain size of the silicon killed steel were sig-

nificant to its lamellar tearing susceptibility. They also suggest that inclusion counting without regard to the type of inclusion is an ineffective method of gaging lamellar tearing susceptibility.

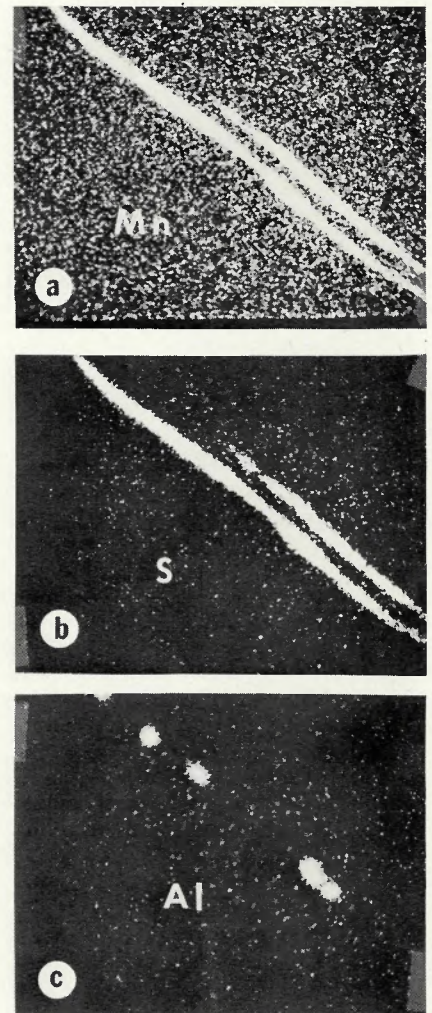


Fig. 15 — Microprobe scans of inclusions in A516-70 steel. (a) manganese scan, (b) sulfur scan, (c) aluminum scan

Table 5 — Strain Age Data for Test Steels

Steel	Testing direction	Properties without strain aging			Properties after 5% prestrain plus aging at 175 C for 1 Hour					
		Y.S., ksi	Elong., %	R.A., %	Y ₁ , ^(a) ksi	Y ₂ , ^(b) ksi	ΔY strain hardening, ksi	ΔY strain aging, ksi	Elong., %	R.A., %
A515-70	Short-Transv.	39.3	16.7	19.4	69.6	78.2	30.3	8.7	12.2	13.8
A515-70	Long.	42.3	31.9	53.7	72.3	80.3	30.0	8.0	23.6	47.7
Mil-S-16113C	Long.	50.0	33.5	62.7	60.2	61.2	10.2	1.0	36.6	68.3
Mil-S-24113C	Long.	58.4	33.6	61.8	70.1	73.0	11.7	2.9	29.9	67.5

(a) Y₁ refers to yield strength after 5% prestrain

(b) Y₂ refers to yield strength after prestrain and 175 C aging

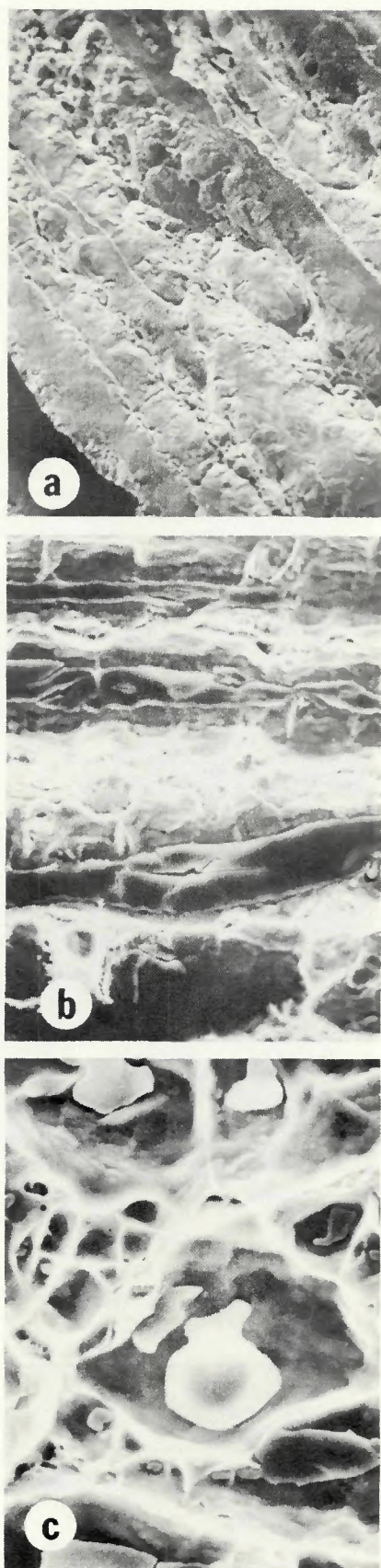


Fig. 16 — Fracture characteristics of A516-70 steel revealed by scanning electron microscopy. (a) dimple fracture area (X200, reduced 8½%); (b) cracked MnS inclusions in fracture area (X1000, reduced 8½%); (c) aluminum oxide inclusions in fracture area (X1000, reduced 8½%)

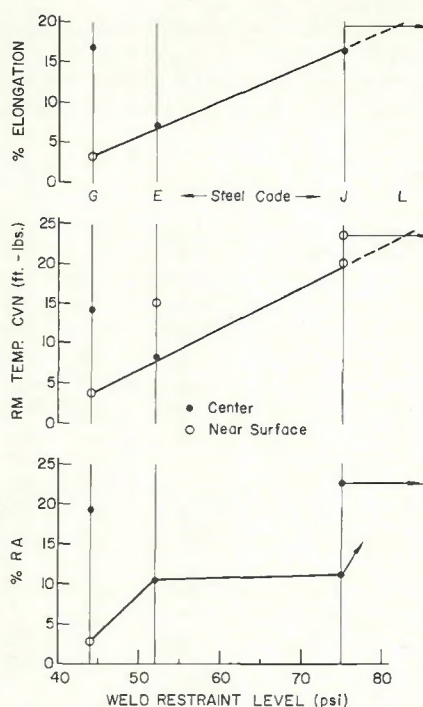


Fig. 17 — Correlation of short-transverse properties with restraint required for lamellar tearing in Lehigh test

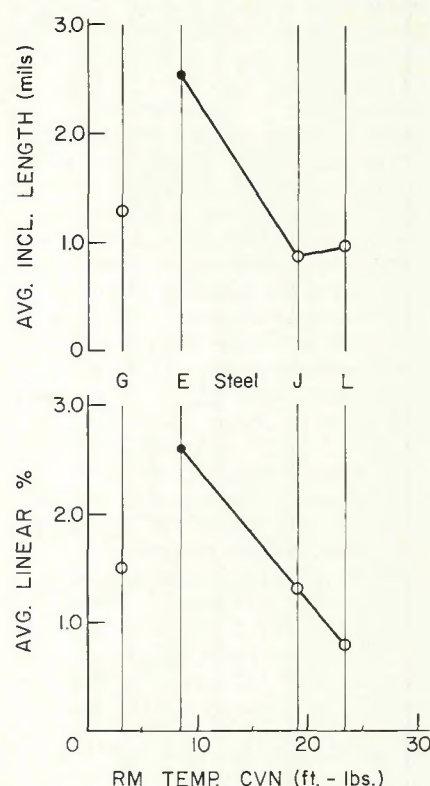


Fig. 18 — Relation of the inclusion count results to the room temperature Charpy V-notch energy absorption

Conclusions

The conclusions to be drawn from this investigation are as follows:

1. The Lehigh lamellar tearing test is a suitable weldability test for quantitatively measuring lamellar tearing susceptibility under laboratory conditions. The test is economical, easy to interpret, suitable for testing a range of lamellar tearing susceptibility in steels, and capable of simulating a variety of practical test conditions.
2. Short-transverse mechanical testing as an indirect measure of lamellar tearing susceptibility can be useful. This investigation showed a clear correlation between the short-transverse elongation or Charpy test energy and the weld restraint level required for lamellar tearing. Erroneous predictions can occur if certain precautions are not exercised. The short-transverse properties vary considerably with the position in the plate. The significant values must be obtained from the region of potential tearing. The location of this region is determined by the design, the plate thickness, the inclusion distribution and the restraint conditions of the service application.
3. Metallographic assessment of physical damage resulting from the early stages of lamellar tearing is

difficult. An easier assessment of this damage can be made ultrasonically while the weldment is under restraint loading. Metallographic sectioning inevitably relieves the restraint stresses and allows the tears to close. The structural damage from these tears will still affect the load carrying capacity of the weldment.

4. The Al-Si killed steels appeared to have better lamellar tearing resistance than the Si killed steels for two reasons: (a) The fine grain structure of the Al-Si killed steels provided a lower brittle-fracture transition temperature and therefore reduced the likelihood of lamellar tearing propagation by quasi-cleavage, and (b) The Al-Si killed steels had no silicate stringers.
5. Silicate stringers were more detrimental in lamellar tearing than a combination of sulfide stringers and aluminum oxide inclusions.
6. The lamellar tearing resistance of Si killed steels can be significantly improved by preheating if it maintains a temperature above the brittle fracture transition temperature.

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Table 6 — Summary of Inclusion Analysis by Quantitative Metallography

	A515-70(G)		A516-70(E)		Mil-S-16113C(J)		Mil-S-24113C(LI)	
	Avg.	Median	Avg.	Median	Avg.	Median	Avg.	Median
Linear %	1.50	1.0	2.60	1.34	1.30	.89	.76	.60
Length/incl (mils)	1.29	1.04	2.52	1.67	.87	.86	.95	.96
Length/group (mils)	2.09	1.64	4.88	2.86	1.98	1.53	1.49	1.20
Transverse mean free path (mils)	23.3		17.9		26.2		42.2	

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