An Evaluation of Factors Significant to Lamellar Tearing

By E. J. KAUFMANN, A. W. PENSE and R. D. STOUT*

GMA or submerged arc welds are consistently more resistant to tearing than are SMA or FCA welds, and two-layer buttering either in a pregrooved plate or on the plate surface is highly effective in suppressing tearing.

ABSTRACT : The mechanism by which lamellar tearing occurs during the welded fabrication of steel structures is by now well understood. Fortunately, lamellar tearing is generally detected during fabrication and has rarely been held responsible for service failures. Its consequences, however, have been severe in a considerable number of structures, provoking expensive repairs and subsequent damage suits. Realization has come slowly that lamellar tearing is not solely a materials problem ; it is, in fact, a design-materials-fabrication problem and can be resolved only by the co-operative efforts of the engineers from all three disciplines.

The investigation reported here was undertaken to determine how fabrication procedures influenced the risk of lamellar tearing in low-alloy high-strength structural steels and what can be done to avoid or mitigate its occurrence.

The results of the investigation may be summarized as follows :

1. Each heat of steel exhibits an inherent sensitivity to lamellar tearing ; this 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 parameters, the welding process was found to exert the most significant influence on lamellar tearing. Welds produced by the GMA process or the submerged-arc process were consistently more resistant to tearing than those made with the SMA or FCA process. The difference apparently resulted from the presence of hydrogen in the electrodes of the later 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 GMA process.

4. Preheating was beneficial to the tearing resistance of GMA welds, but it was especially useful for SMA and FCA welds in 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 GMA and SMA processes and for both carbon steel and low-alloy steel plates.

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E. J. KAUFMANN, A. W. PENSE, and R. D. STOUT are associated with Lehigh University, Bethlehem, Pennsylvania.

6. The use of two-layer buttering either in a pre-grooved plate or on the plate surface was shown to be highly effective in suppressing tearing. This benefit was associated with the tendency of tearing to initiate within 5 mm (0.20 in.) of the fusion line of the joining weld.

7. Preliminary tests suggest that incipient lamellar tears buried from view do not lower the static strength of the joint seriously unless they have propagated sufficiently to be detectible by UT inspection. The plasticity of the joint is lowered by buried tears before its strength is impaired.

Introduction

The mechanism by which lamellar tearing occurs during the welded fabrication of steel structures is by now well understood[2–4]. Tearing is triggered by decohesion of non-metallic inclusions under through-thickness stresses generated by weld contraction. Silicates and sulfides flattened by the rolling operations are the most damaging, and they tend to initiate tears near the weld, in or just outside the heat-affected zone.

Fortunately, lamellar tearing is generally detected during fabrication and has rarely been held responsible for service failures. Its consequences, however, have been severe in a considerable number of structures, provoking expensive repairs and subsequent damage suits. Realization has come slowly that lamellar tearing is not solely a materials problem ; it is, in fact, a design-materials-fabrication problem and can be resolved only by the cooperative efforts of the engineers from all three disciplines.

The investigation reported here was undertaken to determine how fabrication procedures influence the risk of lamellar tearing in low-alloy high-strength structural steels and what can be done to avoid or mitigate its occurrence.

The Experimental Program

Three groups of variables were studied in the investigation :

1. Welding processes.
2. Welding parameters.
3. Geometrical and material factors.

The welding processes included gas metal arc, submerged arc, shielded metal arc, and flux-cored metal arc. The welding parameters examined were heat input, preheat, and electrode strength.

The geometrical and material factors comprised buttering, wide plates, hydrogen potential, and the steel grade. In addition, some tests were devised to evaluate the effect of buried lamellar tears of controlled size on the joint static strength at room temperature and at $-84°C$ ($-120°F$).

Preliminary Testing

Test Method : The Lehigh cantilever lamellar tearing test developed previously[5] was used as the test method. It provides facilities for depositing a multipass weld in a V-groove between the test specimen and a beveled 60-mm (2 in.) thick beam set at right angles to it. The beam can be loaded by a hydraulic jack to produce a desired level of tension stress on the weld joint in the thickness direction of the specimen plate.

The test configuration is shown in Fig. 1. Two measuring devices are incorporated into the test set-up : a load cell to measure the load applied to the end of the cantilever by the jack, and a displacement gauge to detect the movement across the weld between the joint members induced by welding thermal effects and the external loading. Loading to the desired stress level was obtained by measuring the height of the deposit after each complete layer was deposited and calculating the required load as :

P = (stress × weld area × distance of weld centre from beam bottom)/(length of cantilever)

By testing a series of specimens over an appropriate range of stress levels a critical level of restriant is deter-

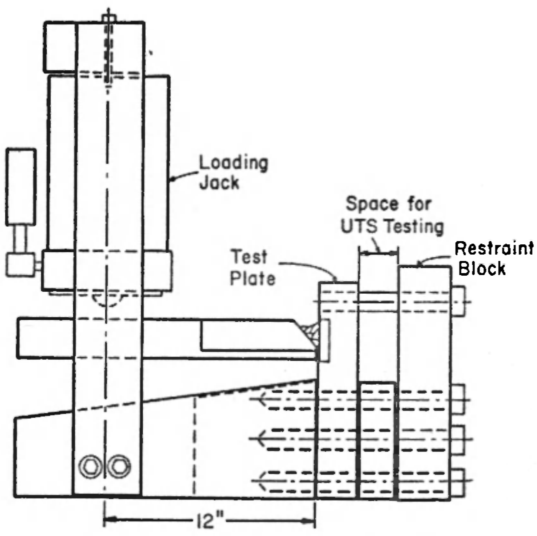


Fig. 1—Lehigh lamellar tearing fixture

mined at which the weld joint can be completed without premature failure but will fail at a postweld load only slightly above the stress level used in making the test. This is designated the critical restraint level ; it can be used as an index to measure the relative lamellar tearing sensitivities resulting from variations of materials and welding procedures.

Where possible, multiple specimens were tested over the necessary range of restraint stresses to determine the critical restraint level and strain for a given set of test parameters. Thus, when the critical restraint-level is listed in a table, it comes from a series of 3-5 individual tests. When high resistance to lamellar tearing was observed (so that the critical restraint was above the test jig capacity), the restraint level imposed during welding and the postweld stress required to fracture the joint were recorded for individual tests as evidence of the resistance to lamellar tearing. This point should be kept in mind in studying the data presented in the tables.

Since lamellar tearing is associated with the limited ability of materials to plastically deform in the through-thickness direction under the forces generated by weld contraction, a second indicator of susceptibility to lamellar tearing is the displacement or "strain" that the joint has undergone before failure at the critical restraint level. The product of the critical stress and the concomitant strain, termed the energy index, is an arbitrary measure of the energy absorbed by the joint during the weld fabrication. This has previously[3] been found to be a useful composite indicator of the strength and ductility of the joint under welding constraints. Generally, all three of these indicators show the same trends, but sometimes to varying degrees. Where available, the strain and energy index values are listed with the critical restraint levels as additional information.

The GMA process was used as a standard, with 1.1 mm (0.04 in.) E705-3 steel filler metal wire to produce a high-strength deposit. Metal was deposited at 300 amperes (A) and 30 volts (V) with 2% oxygen in argon as the shielding gas. Normal travel speed was 30 cm per min. (12 ipm) for a heat input of 18 kilojoules per cm. (45 kJ/in.) Other heat inputs were obtained by altering the travel speed.

Selection of Test Steel : It was agreed that the steel to be tested should be A572 and A588 grades with as

Table 1 Calibration of Candidate Steels for Testing Program ([a]) ([b])

Steel	Thickness ([d])	Weld restraint level, MPa (ksi)	Postweld failure stress, MPa (ksi)	Notes
1. (A588) Grade A	64 mm	380 (55)	655 (95)	Weld metal failure
		380 (55)	550 (80)	6 mm surface removed
		380 (55)	515 (75)	13 mm surface removed
		380 (55)	450 (65)	25 mm surface removed
2. (A572) Grade 50	45 mm	485 (70)	585 (85)	No failure
3. (A572) Grade 50	51 mm	485 (70)	484 (70)	Lamellar tear
4. (A572) ([c]) Grade 50	45 mm	345 (50)	585 (85)	Lamellar tear
		345 (50)	515(75)	13 mm surface removed
		345 (50)	345 (50)	23 mm surface removed
		345 (50)	275 (40)	23 mm surface removed (failed after 6th pass)

([a]) (GMA process, 30V, 300A, 30 cm/min. (12 ipm) travel speed, argon + 2%0_2, 9 passes)

([b]) Note : The data are obtained from individual test specimens

([c]) Steel 4 selected as the test steel. Composition (wt-%) : 0.18 C, 1.32 Mn, 0.011 P, 0.025 S, 0.28 Si, 0.13 Cr, 0.10 Ni, 0.04 Mo, 0.06 V, 0.13 Cu and 0.034 Al. Mechanical properties : yield strength—410 MPa (59.0 ksi), tensile strength —620 MPa (89.0 ksi), elongationin 51 mm (2 in.)—28.5%.

([d]) 25.4 mm = 1 in.

minimum yield strength of 345 MPa (50 ksi). After tests on plates from 4 candidate heats had indicated that they were relatively resistant to lamellar tearing, the most susceptible heat was tested with various depths of surface metal removed.

The results shown in Table 1 demonstrated a noticeably greater sensitivity to tearing of metal below the surface layer. Incidentally, they also illustrated the limitation of through-thickness tensile tests. These tests measure mid-thickness ductility, which may be unreliable in predicting the tearing tendency of the surface layers where tearing forces are the greatest.

For the study of welding variables, it was decided to weld against the mid-thickness location of split plates. The composition and mechanical properties of the A572 Grade 50 steel chosen are also listed in Table 1. The inclusions found in the A572 steel are shown in Fig. 2, and the path of tearing in Fig. 3.

Effect of the Welding Process

Relatively little study of the welding process as a factor in lamellar tearing has been conducted previously, particularly without involving heat input as a concomitant variable. Four processes were examined in this study, all with the same heat input—18 kj per cm. The results of the test series are shown in Table 2. Since the tearing susceptibility of the steel welded with the GMA process in argon $+2\%\ O_2$ was adopted as a control standard for comparision, it is convenient to compare the other processes on this basis.

The most significant feature of the results is that there are notable differences in tearing sensitivity among the welded joints produced by the four processes. The E7018 electrode welds showed a reduced critical restraint stress and a large loss in strain to fracture compared to the GMA welds. The FCA welds displayed erratic behavior but on the average were inferior to the GMA welds. The submerged arc welds were stronger than the GMA welds but not as ductile. The increased strength appeared to come from a favourable toe contour that enlarged the supporting area next to the base metal HAZ, as shown by Fig. 4.

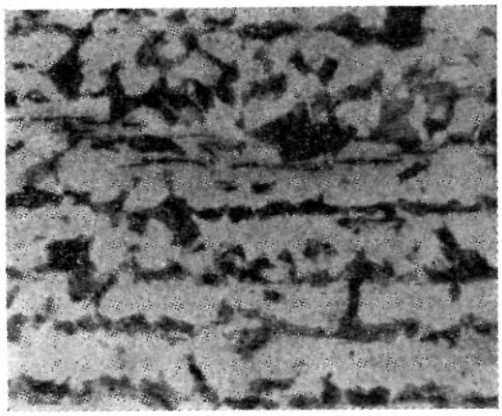


Fig. 2—Microstructure of the mid-thickness of A572 steel showing inclusions. Nital etch. X260 (reduced 50% on reproduction)

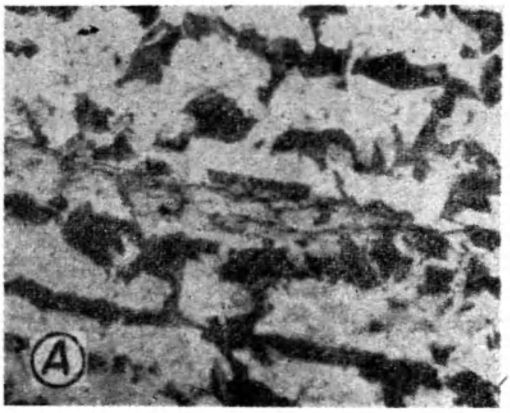
It was demonstrated by tests reported in a late section that the variations among processes were attributable to an important degree to the presence of hydrogen in the SMA and FCA processes.

Effect of Welding Parameters

Heat Input: Tests were run on GMA welds deposited with heat inputs ranging from 12 to 60 kilojoules per cm. The influence of heat input (Table 3), failed to display any trend. It should be noted that heat input was varied by means of travel speed only. It is possible that current increases would not exert the same effect on tearing as reduced travel speed. In any event, the control of heat input does not appear to be a promising technique for lessening lamellar tearing.

Table 2–Effect of Welding Process on Lamellar Tearing (A572 steel, split, heat input 18 kJ/cm, 6 passes except SMA was 9 passes)

Process	Consumables	Critical welding restr. level, MPa (ksi)	Strain across weld, mm.	Energy index $\sigma.\epsilon$	Notes
GMA	E70S-3 A $+ 2\%\ O_2$	335 (48)	0.12	40	Control standard
					Electrodes at 100°C
SMA	E7018	310 (45)	0.07	22	3 mo.
FCA	E70T-1	275-345 (40-50)	0.05	16	Results scattered
SA	EM13K wire, 85 flux	415 (60)	0.10	40	—



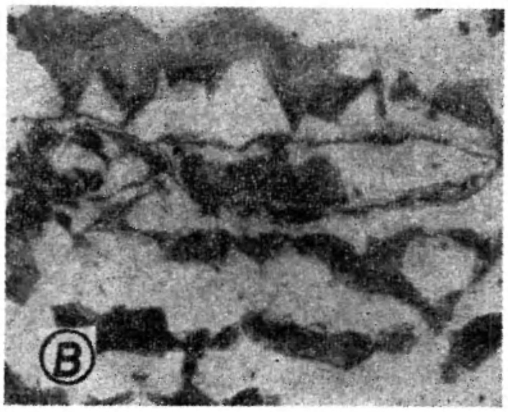


Fig. 3—Incipient lameller tears in A572, illustrating their association with inclusions and their tendency to propagate in the preeutectoid phase. Nital etch. A—X250; B—X500 (reduced 41% on reproduction)

Preheat : To study the consequences of preheating and interpass temperature for welding, test welds deposited by the GMA, SMA, and FCA processes were prepared. As shown in Table 4, lamellar tearing resistance was improved by preheating for all three processes but it was greater for the SMA and FCA processes, perhaps because of the hydrogen potential present in

Fig. 4—Cross section of the submerged arc weld showing the rounded contour of the toe-which favoured tear resistance

the arc atmosphere of these processes. As pointed out later, preheating in service structures may not be so effective as shown here if local preheating adds to the final contraction strains in a restrained joint.

Electrode Strength : If the strength of the weld metal deposited is lowered, it can be expected that the more readily induced strain in the weaker weld metal will relieve the base metal of some of the total size adjustment imposed on it. Unfortunately, this expedient is limited by the range of strengths obtainable in weld metal as well as by design requirements from the joint. Nevertheless, one series of GMA welds was made with C-Mn EM13K filler metal instead of the low-alloy filler metal normally used. From Table 5 it can be seen that the trend was indeed toward improved resistance to tearing with lower strength weld metal.

Table 3 Effect of Heat Input on Lamellar Tearing (A572 steel, split, GMA process)

Heat input, kJ/cm	Critical welding restr. level, MPa (ksi)	Strain across weld, mm	Energy index $\sigma.\epsilon$	No. of passes	Current and travel speed
12	345 (50)	N.A	N.A.	9	300A, 45 cm/s
18	335 (48)	0.12	40	6	300A, 30 cm/s
38	310 (45)	0.13	40	5	300A, 15 cm/s
60	345 (50)	0.14	48	3	325A, 10 cm/s

Table 4 Effect of Preheating on Lamellar Tearing (A572 steel, split, 18 kJ/cm)

Electrode	Preheat and interpass temp.	Critical welding restr. level, MPa (ksi)	Strain across weld, mm ([a])	Energy index $\sigma.\epsilon$
GMA	20°C (68°F)	335 (48)	0.12	40
(E70S-3)	125°C (257°F)	380 (55)	0.16	59
SMA	20°C (68°F)	275 (40)	0.07	22
(E7018)	150°C (302°F)	345 (50)	0.09	31
FCA	20°C (68°F)	275-345 (40-50)	0.05	22
(E70T-1)	150°C (302°F)	410 (60)	0.08	33

([a]) 25.4 mm = 1 in.

Table 5 Effect of Electrode Strength on Lamellar Tearing (A572 steel split 18 kJ per GMA process)

Process	Weld metal Brinell hardness	Critical welding restr. level, MPa (ksi)	Strain across weld, mm ([a])	Energy index $\sigma.\epsilon$
PE70S-3	228	335 (48)	0.12	40
EM13K	190	365 (53)	0.14	51

([a]) 25.4mm=1 in

Geometrical and Composition Effects

Buttering : Since lamellar tearing initiates in the base metal in or just outside the heat-affected zone (HAZ), generally within 5 mm (0.20 in.) of the weld interface, replacement of this base metal by weld metal or covering it with a buffer layer of weld metal has been used to reduce susceptibility to tearing. The effectiveness of the buttering technique was examined for the test steel. A transverse groove 6 mm deep and 38 mm (1½ in.) wide was cut across the test piece at the location where the weld between the specimen and the cantilever beam was to be deposited. Eight passes of E7018 weld metal were deposited with 5 mm (0.20 in.) diameter electrodes at 24V, 240 A, and 15 cm/min (6 ipm) travel speed to fill the groove with two layers of weld metal.

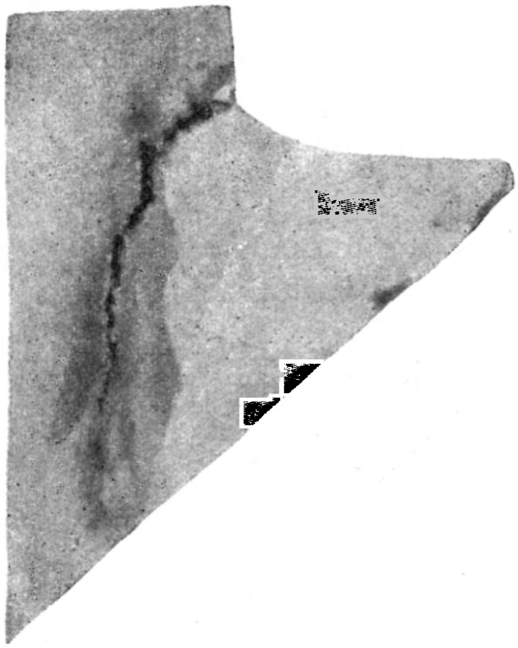


Fig. 5—Cross section of a weld joint on a buttered groove. Here the buttering did not extend beyond the toe of the joining weld, but tearing avoided the buttered region

The first specimen loaded during welding to 345 MPa (50 ksi) required a postweld load of 450 MPa (65 ksi) for failure. A cross section of the failure (Fig.5) reveals that the base metal under the buttered layers tore out starting near the toe of the test weld. This occurred because the toe of the joining weld virtually coincided with the edge of the buttered layers. Nonetheless, there was a gain in tearing resistance. In subsequent specimens the buttered groove was widened to clear the

Table 6 Effect of Buttering on Lamellar Tearing (A572 steel, split, buttered with E7018, Joining weld at 18 kJ/cm, GMA process) ([a])

Buttered pad ([b])	Weld restraint level, MPa (ksi)	Postweld failure stress, MPa (ksi)	Strain across weld, mm ([b])	Energy index $\sigma.\epsilon$
None	335 (48)	335 (48)	0.12	40
6 mm deep, 38 mm wide	345 (50)	450 (65)	N.A.	N.A.
6 mm deep, 38 mm wide	415 (60)	585 (85)	0.22	91
6 mm deep, 45 mm wide	345 (50)	520 (75)	0.30	104
6 mm deep, 45 mm wide	415 (60)	520 (75)	0.34	140
6 mm high 80 mm wide	335 (48)	440 (64)	0.20	67
6 mm high, 80 mm wide	415 (60)	530 (77)	0.29	120
6 mm high, 80 mm wide	485 (70)	585 (85)	0.25	121

([a]) Data obtained from individual test specimens.
([b]) 25.1 mm = 1 in.

toe of the joint weld. As evident in Table 6, these tests loaded at 345 MPa (50 ksi) or 415 MPa (60 ksi) withstood postweld loads of 520 MPa (75 ksi) before failure. Thus, the benefit of buttering was clear.

An additional group of tests was run to demonstrate the effect of buttering placed on the base plate surface rather than in a prepared groove. The data from these tests, also listed in Table 6, confirm that surface buttering is equally effective in suppressing lamellar tearing. Note especially the enhanced strain developed across the weld before failure. Views of the tearing path, shown in Fig. 6, attest that much larger loads and deformations are required to effect a joint failure than those for unbuttered steel.

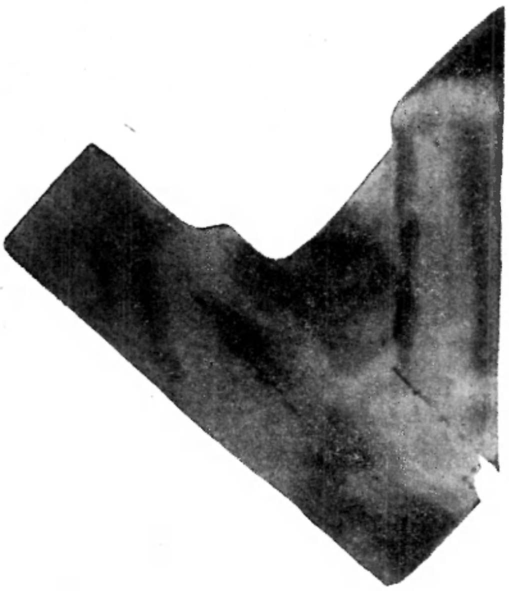


Fig. 6—Cross section of a weld joint on a specimen previously surface-buttered. Tearing was suppressed by the intervening buttered layer

Wide Plate Tests : The question was raised whether welding the cantilever beam to a wide test plate would increase the tendency to tear because of a higher restraint condition. Therefore, the 76 mm (3 in.) wide cantilever beam was welded to a 150 mm (6 in.) wide test plate, with 50 mm (2 in) run-off tabs at the sides of the beam.

The results in Table 7 indicate a raised, not lowered, resistance to lamellar tearing. The higher loads at failure were accounted for by the added support provided by the longer weld. Since fabrication welds joining a beam to a wider column would have a similar configuration, the results are applicable to such structures. Thus, a concern about higher restraint effects in welds made to a wide section does not appear to be warranted.

Tests on A588 *Steel :* In some of the early occurrences of lamellar tearing in thick-section fabricated structures, A588 grades of steel were reported to be involved. This study was undertaken to assess the validity of opinions that ASTM A588 steel, particularly in heavy plates, is more susceptible to lamellar tearing than other steels such as ASTM A572. Six heats of the grade were collected and tested.

Table 8 summarizes the results, which indicate that none of the heats showed susceptibility to tearing. This outcome is evidence that steels produced to current

Table 7 Effect of Plate Width on Lamellar Tearing (A572, split, GMA, 18 kJ/cm) ([a])

Plate Width	Weld restraint level, MPa (ksi)	Postweld failure stress, MPa (ksi)	Strain across weld, mm ([b])	Energy index $\sigma.\epsilon$
75 mm (3 in.)	335 (48)	335 (48)	0.12	40
150 mm (6 in.)	345 (50)	485 (70)	0.25	86
150 mm (6 in.)	345 (50)	485 (70)	0.35	120

([a]) Data obtained for indivudual test specimens.
([b]) 25.4 mm = 1 in.

Table 8 Lamellar Tearing Tests on A588 Grade A Steel Plate (GMA Process, 18 kJ/cm) ([a])

Heat	Thickness	Welding restraint level, MPa (ksi)	Postweld stress, MPa (ksi)
1	64mm	380 (55)	550 (80)
2	127	485 (70)	605 (88)
3	76	620 (90)	620 (90)
4	45	550 (80)	620 (90)
5	76	550 (80)	690 (100)
6	51	655 (95)	655 (95)

([a]) No failures.

ASTM A588 steel specifications exhibit no unusual sensitivity to lamellar tearing. As a result, they would be expected to behave in a manner similar to the carbon steels when subject to welding conditions that promote lamellar tearing.

Further Studies of Hydrogen

The behavior of the tests welded with the four welding processes, coupled with some work done previously, suggested strongly that hydrogen is a significant contributor to the generation of lamellar tearing in welded steel joints. Some additional tests were undertaken to probe the concentration of hydrogen required to influence tearing. Two techniques were applied :

Table 9 Effect of Hydrogen on Lamellar Tearing (A572 Steel, split. 18 kJ/cm)

Process	Variable	Critical welding restr. level, MPa (ksi)	Strain across weld, mm ([a])	Energy index
GMA	E70S-3 dry argon	335 (48)	0.12	40
	Argon + 1% H_2O	205 (30)	0.07	14
SMA	E7018 (100°C oven)	310 (45)	0.07	22
	E7018 (humidified 24 h)	245 (35)	0.05	12
	Same with 150°C preheat	415 (60)	0.10	41
	E7010	245 (35)	0.01	2.5

([a]) 25.4 mm = 1 in.

Table 10 Mechanical Tests on Specimens with Buried Lamellar Tears (A572 Steel, split. 18 kJ/cm) ([a])

Test temp, °C (°F)	Failure stress MPa (ksi)	Strain (across weld), mm ([b])	Energy index	Lam. tearing, %
−83 (−117)	350 (51)	0.5	175	60
−84 (−119)	305 (44)	1	305	mixed (50?)
−62 (−80)	205 (30)	0.6	120	80

([a]) Data are obtained from individual tests.
([b]). 25.4 mm = 1 in.

1. The addition of moisture to the argon shielding gas of the GMA process, and

2. Variation in the moisture content of E7018 electrodes and use of high-hydrogen E7010 cellulosic electrodes.

As shown in Table 9, the addition of moisture to the GMA shielding gas produced tears at greatly reduced loads and attendant weld strains compared to dry argon. Similarly E7018 electrode, which when dry produced welds with tear resistance approaching that of the GMA welds, lost this ability when humidified for 24 hours. A preheat of 150°C (302°F) not only restored tearing resistance but actually improved it. As expected, welding with E7010 cellulosic electrode, which supplies a high hydrogen potential, resulted in low critical restraint levels and markedly reduced weld strains.

It is possible that the A572 steel, because of its hardenability, developed hydrogen cracking that helped trigger lamellar tearing. However, postweld loading to failure was done within 15 min of completing the weld and at a temperature about 50°C (122°F), so that cold cracking would be limited. Also the effect of hydrogen on tearing had previously been demonstrated on a low carbon steel, A283, of low hardenability. Thus, the effect of hydrogen appears to be associated with embrittlement rather than with cold cracking.

Effect of Buried Tears on Static Strength

A concern in welded fabrication is the possible loss in mechanical strength of joints containing buried incipient lamellar tears. Work was undertaken to learn whether such buried flaws could be produced deliberately in the test weld joint so that their effect on static strength could be measured.

Exploratory tests showed that a narrow range of loading encompasses the transition from no tearing to complete failure—Table 10 and Fig. 7. Also, in UT testing during loading, the noise level from the inclusion density obscured the signals from tears.

One useful symptom of tearing was the failure of the joint to reload itself after a new pass was deposited and contracted during cooling. Sound welds consistently relax the applied load during the expansion from the heat of welding and then reload to the applied stress or higher when they cool and contract. This fact established the critical load to be used. However, it did not permit precise control of the size of the defect produced.

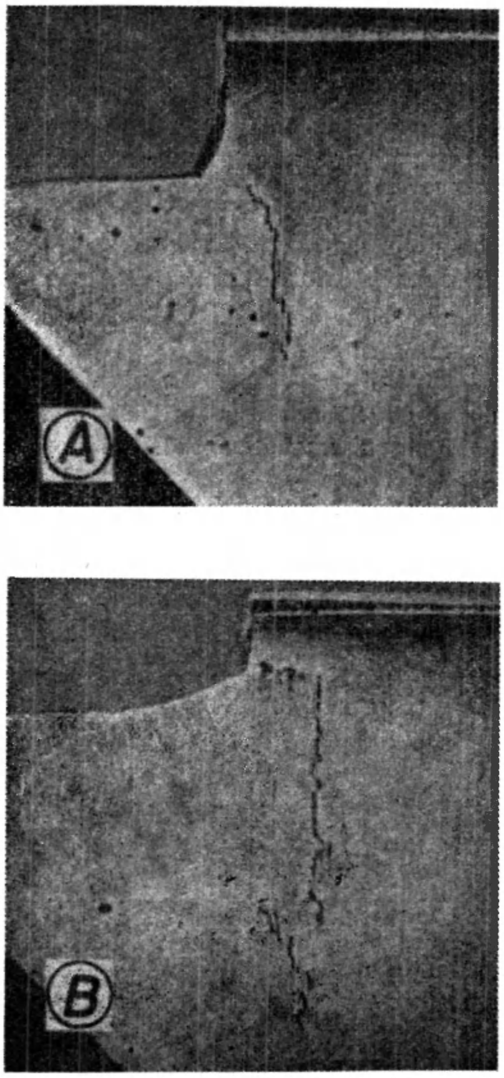


Fig. 7—Cross section from welds containing buried lamellar tearing showing the sensitivity to the imposed stress level. A—47 ksi load, B—48 ksi load

After further trials, a fairly reliable technique was developed to obtain partial tearing in the joint. The sequence of loading after each weld pass was as follows :

- 1st pass : load to critical restraint level—315 (45 ksi) for the A572.
- 2nd pass : restore load to 315 MPa (45 ksi).
- 3rd pass : load until yielding is observed.
- 4th to 6th pass : maintain load at 3rd pass level.

The effect of this procedure was to initiate tearing in the early passes but to interrupt it in the top layer

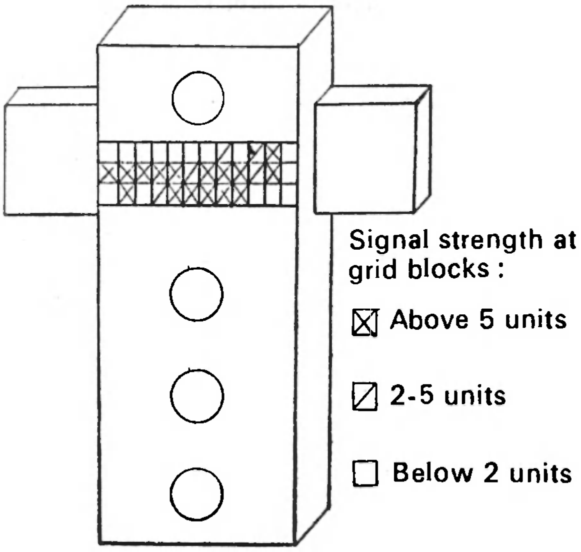


Fig. 8—Results of ultrasonic scan of welded joint

(4 to 6th passes) by not raising the load to match the increase in supporting weld area.

A specimen prepared by the above method was surveyed with a 5 MHz, 6 mm crystal from the back side with the instrument set to display reflections within 6 mm of the welded surface. The signals were partially obscured by background noise from non-metallics, which limited the ability to determine the exact dimensions of the tears. No attempt was made to relate the instrument settings to NDE calibration standards. The data obtained are shown in Fig. 8 based on the response recorded on the basis of a 6 mm grid scribed opposite the weld. It is clear that the middle third of the weld joint contained extensive tearing, and the lower third less tearing. The top layer was free of tears according to the UT results. Cross sections taken from a duplicate specimen show the nature of the tearing—Fig. 7.

After the UT scan the specimen was loaded to failure, Failure occurred at 270 MPa (39 ksi), and was completely lamellar tearing. This is a surprisingly high stress considering that nearly 40% of the weld area was blued by the welding heat and must have formed lamellar tears during fabrication. The discoloured area is shown in Fig. 9.

Three additional specimens were prepared with buried tears and tested at low temperature. The results are listed in Table 10. The first specimen, with 60% of the fracture showing lamellar tearing, supported 350 MPa (51 ksi) before failure at —83°C (—117°F). This stress level, close to the yield strength, is remarkable considering how much lamellar tearing had

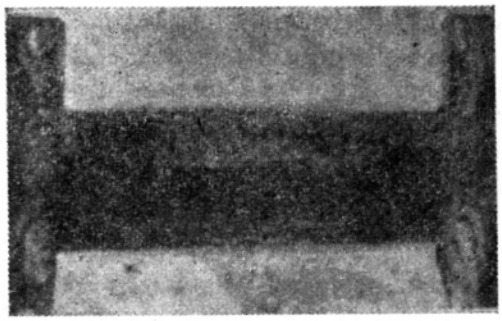


Fig. 9—Fractured specimen showing discolored area which developed lamellar tearing during welding under restraint

occurred. The second specimen, showing a fine mixture of lamellar tears and brittle fracture that could not be assessed for % lamellar tear, supported 305 MPa and similar ductility to the first specimen. The third specimen was estimated to have 80% lamellar tearing but required 205 MPa (30 ksi) for failure.

All in all, the load carrying ability of welded joints containing buried lamellar tears is surprisingly high under low-temperature static loading. The behavior in dynamic loading or fatigue may be quite different.

Summary

The results of the investigation may be summarized as follows :

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 the parameters of welding, the welding process was found to exert the most significant influence on lamellar tearing. Welds produced by the GMA process or the submerged arc process were consistently more resistant to tearing than those with the SMA or FCA 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 GMA process.

4. Preheating was beneficial to the tearing resistance of GMA welds, but it was especially useful for SMA and FCA welds in counteracting the damaging effects

of hydrogen. The use of pre-heating 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 in the arc atmosphere was deliberately varied demonstrated clearly the deleterious effect of hydrogen on lamellar tearing resistance. This behaviour has been shown for both the GMA and SMA processes and for both carbon steel and low-alloy steel plates.

6. The use of two-layer buttering either in a pre-grooved plate or on the plate surface was shown to be highly effective in suppressing tearing. This benefit was associated with the known tendency of lamellar tearing to initiate within 5mm of the weld interface of the joining weld.

7. Preliminary tests suggest that incipient lamellar tears buried from view do not lower the static strength of the joint seriously unless they have propagated sufficiently to be detectible by UT inspection. The plasticity of the joint is lowered by buried tears before its strength is impaired.

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