Lamellar Tearing and the Slice Bend Test

BY M. L. DRURY AND J. E. M. JUBB

Authors establish the basis for a test suitable for plant use by unskilled personnel

ABSTRACT. The lack of ductility through the thickness of steel plate has given rise to lamellar tearing in the plate, when it is subjected to weld shrinkage stresses in the thickness direction. Research in the last decade into lamellar tearing has led to a wide variety of tests, destructive and non-destructive. The latter has had such limited success that a suitable destructive test has been sought. It is suggested that the slice bend test provides the most information for a given price. Six hundred tests on ten steels have shown the power of discrimination of the test and a correlation with through-thickness tensile tests which have been used with some measure of success to assess the susceptibility of steels to lamellar tearing.

Introduction

Nondestructive testing to assess ductility in the thickness direction has failed[1, 2] and although alternative procedures are being examined, designers and fabricators have to rely on destructive tests at the present time.

A range of destructive tests[3, 4] with and without welding has been suggested for dealing with this problem and the through-thickness tensile test has proved to be the most acceptable. The latter suffers from a small volume fraction of material in the gauge length and requires skill in manufacture and testing.

M. L. DRURY and J. E. M. JUBB are associated with the Cranfield Institute of Technology, Cranfield, Bedford, United Kingdom

The slice bend test[5, 6] was developed to meet the following criteria for use in production, development and research.

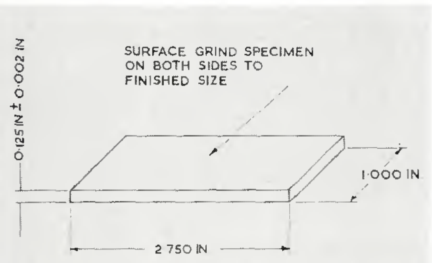

Fig. 1 — Dimensions of slice bend test

1. The test specimen should be simple and cheap to produce.
2. The test should initially provide an assessment of susceptibility to lamellar tearing on a comparative basis.
3. The equipment required should be low in cost, and cost little to operate and maintain.
4. The test should be simple so that unskilled labor could be used to perform the test and interpret results.
5. The volume of material in the specimen should be as great as possible to improve its statistical significance.
6. It should be possible to produce a tear in the specimen, measure its length and relate this to the nominal strain in the region of the tear.

Further criteria were added, mainly because of their importance in laboratory investigations:

7. Variables such as heat treatment, simulated weld cycles, etc., should be readily applicable and the effects amenable to evaluation.
8. The specimen should provide relevant fracture surfaces for examination, and allow comparison with fracture surfaces from actual fabrication failures.

Practical Aspects of the Test

The Slice Bend Specimen

Specimen thickness was selected so as to contain a material volume representative of the material under test, but sufficiently thin in comparison with the test width, to allow bending with a small applied force. The thickness was therefore fixed at 0.125 in. (3.175 mm).

The specimen width was set at 1.000 in. (25.4 mm) since this was the thickness of the original plates. The specimen length was arbitrarily set at 2.750 in. (70 mm), but there seems to be no reason why this could not be increased and so test more plate. This investigation was limited to the chosen size as this could be accommodated adequately at all stages of specimen preparation and testing.

The preparation of the specimen to the dimensions given in Fig. 1 was carried out by various production methods, owing to the quenched and tempered nature of six of the steels under investigation. All specimens however underwent the same final grinding operation to produce the thickness of the specimen. Grinding took place at 45 deg to the longitudinal axis of the specimen, reducing heat input. The ground surface finish was better than the 8 micron Centre Line Average value.

The specimen layout was such that material at various depths in thicknesses, greater than 1.000 in. (25.4 mm) would be tested, see Figs. 2 and 3. The dimensions of the tensile test specimen (Hounsfield No. 11) are given in Fig. 4.

Specimen Test Rig

The slice bend testing rig was designed with the following terms of reference:

1. The capital cost of equipment had to be low.
2. The major parts added for carrying out the test, i.e., the former and the die block, see Fig. 5, should be of simple construction and easily replaced.
3. Specimens should be easily fitted into the rig and removed from it during or after testing.
4. A means of direct measurement of the depth of penetration of the former into the die block should be provided.

Using these criteria a single acting hydraulic press of 2 tons (2,000 kg) capacity with a ram movement of 1.5 in. (38.1 mm) would be adequate.

The former, Fig. 6, and the die block, Fig. 7, were bolted to the fixed platform and the ram head respectively. For the initial testing the former and die block were made from standard stock pieces of mild steel to reduce the cost and allow modifications to the design to be made if necessary. For production testing the former and the die block would be manufactured from a steel suitable for case hardening. The complete assembly of the press with the die block, former and a specimen under test are shown in Fig. 8.

To meet the last of the criteria, item 4, a dial gage indicator was rigidly attached to the fixed platform and adjusted to read the ram head movement during testing. The indicator is shown in Fig. 5.

Sequence of Specimen Testing

The test rig was zeroed using a setting piece in place of the normal specimen, this piece being accurately made to + or − 0.0005 in. (0.0127 mm). The specimens were then tested by placing in the rig and subjecting each in turn to increasing deflections by the former into the die block, the deflection being increased in 0.010 in. (0.254 mm) increments. After each increment the tensile surface of the specimen was examined, in the first instance for surface failure, and then for a 1/8 in. (3.175 mm) flaw.

The point of surface breakdown and the 1/8 in. (3.175 mm) flaw were the criteria used for determining susceptibility to lamellar tearing and these are examined in the discussion. An 1/8 in. flaw could normally be detected by ultrasonics.

Results

The ten steels were numbered and chemically analyzed, the analysis of each steel being detailed in Table 1. It will be seen that the carbon content of all the steels lay within 0.11 to 0.17%. In the case of the two steels 5665 and 5758, however, the manganese content was considerably lower than the other steels. The silicon content of the other two mild steels, M.S.1. and M.S.2. was significantly low, while that of the semi-killed steel, S.K.1, was very high. The remaining steels had between 0.11 and 0.26% silicon. The nickel content of steels 5665 and 5758 was also higher than in the other steels.

Table 2 further identifies the type of plates used by test number. This table includes the thickness of the plates tested. In the case of the Q1(N) and QT35 steels inclusions were assessed at a magnification of X250 counting nonmetallic inclusions greater than 2 microns in length and choosing 36 random fields for each material. These values are also given in Table 2.

The tensile tests carried out on the Q1 (N) and QT35 steels were divided into four groups:

1. Percent elongation in the rolling direction.
2. Percent elongation in the thickness direction.
3. Percent reduction in area in the rolling direction.
4. Percent reduction in area in the thickness direction.

The results of the tensile tests were summarized on the four graphs shown in Figs. 9-12. By using these graphs it was possible to compare the six steels in a given direction for a given property. It was further possible to compare the results of a given steel in one direction with results in the second direction, considering the graphs independently.

The graph of tensile tests in the thickness direction for % elongation, Fig. 9, compares nine specimens taken from each of the six steels that were tested. The steels showed differences, but the total variation in elongation was small. However steels 5665 and 5758 appeared the most

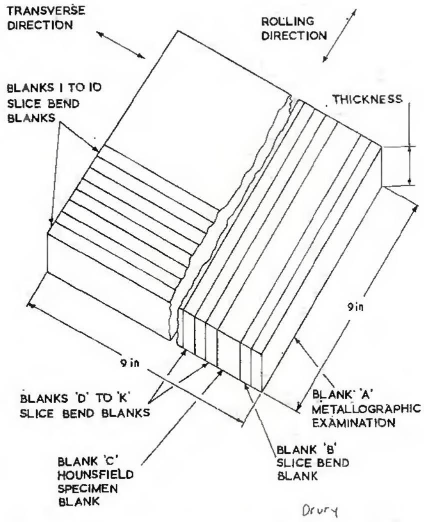

Fig. 2 — Layout of specimen blanks in 9 x 9 in. plate

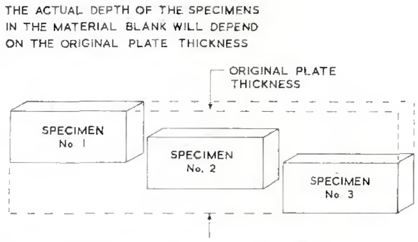

Fig. 3 — Layout of slice bend tests in material blank

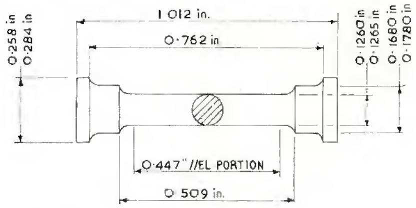

Fig. 4 — Tensile test specimen (Hounsfield No. 11)

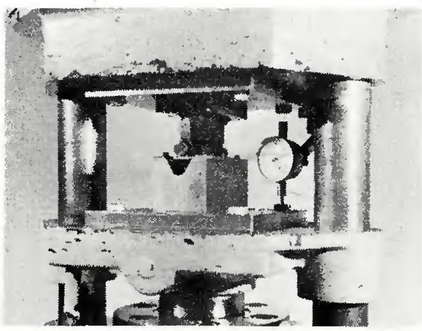

Fig. 5 — Slice bend specimen between former and die block

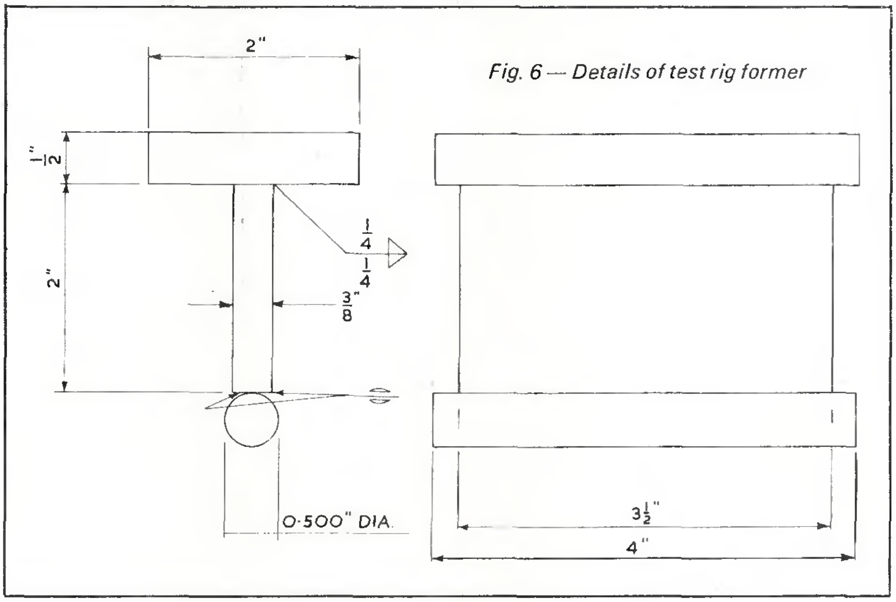

Fig. 6 — Details of test rig former

ductile, while steel 825 showed overall the least ductility. Steels 4981 and 9639 appeared to have similar ductilities.

The tensile test results of % elongation in the rolling direction, Fig. 10, lay mainly in a very narrow band, only some eight divisions wide; this made any differences in the steels very difficult to assess, so the steels could be considered to have basically the same ductility in this direction.

When the % reduction in area results were plotted these gave two further graphs, Figs. 11 and 12. The interpretation of results from these graphs was easier due to an increase in the width of the band within which the results lay. However, it was still difficult to establish definite differences in the steels when the rolling direction values were compared. Steels 5665 and 5758 did appear generally to have larger % reductions in areas than the other steels.

The graph of % reduction in area in the thickness direction, Fig. 11, gave the most information of all. Here the steels were distributed in a wide band some 66 divisions wide, and definite differences in the steels could be seen. Steels 5665 and 5758 were the most ductile, 5758 being possibly the more ductile of the two. Steel 825 showed the least ductility of the six steels tested, and steels 4981 and 9639 showed similar ductilities.

From the graphs it became obvious that to use the rolling direction to discern between steels for susceptibility to lamellar tearing would be difficult, whether % elongation or reduction in area were used. The thickness direction testing revealed markedly different results compared with those in the rolling direction, and here it was possible to classify the steels. However it is the authors' opinion that % reduction in area gives a better indication of susceptibility to lamellar tearing and % elongation. These findings bear out those of other workers such as Farrar.[1]

From the ten steels examined, slice bend specimens were taken in the two main plate directions, i.e., rolling and transverse directions, see Fig. 13. These specimens were then tested as described previously. The results obtained for 1/8 in. (3.175 mm) flaw in the tension surface of a large percentage of the specimens tested in the two directions are given in the graphs, Figs. 14 and 15.These graphs allowed determination of the tests' validity for susceptibility to lamellar tearing in a given steel plate.

The two graphs, Figs. 14 and 15 showed that there were major differences between the ten steels, when ductility was measured by the amount of deformation that could be given to the steel to produce a 1/8 in. (3.175 mm) flaw in the tension face of the specimen. It was also noted from the graphs that there was a variation in the amount of deformation necessary to produce the given flaw, depending on whether the specimen was taken from the rolling direction or the transverse direction. Results were generally higher in the transverse direction compared with those in the rolling direction.

The examination of the steels was completed by the use of optical and stereo-scanning microscopes. This provided information on the surface of the fractures produced by over deforming the specimens. Grain structure and inclusions were also studied to see if this could provide any information to back up any findings. The mechanism of cracking was revealed by low power examination of the tension face of slice bend specimens using the stereo-scanning microscope. Owing to the large volume of data obtained from this work only certain information will be considered and will be referred to in the discussion.

Discussion

The slice bend tests carried out on the ten steels showed that these steels could be deformed by various amounts before fracturing of the surface occurred, the amount of deformation depending on how effective the matrix material was in yielding rather than fracturing. Where the matrix of the material contained a significant amount of inclusions, there was a possibility of these reducing the yielding capacity of the material and thus leading to the early failure of the matrix material.

The effect of the inclusions was

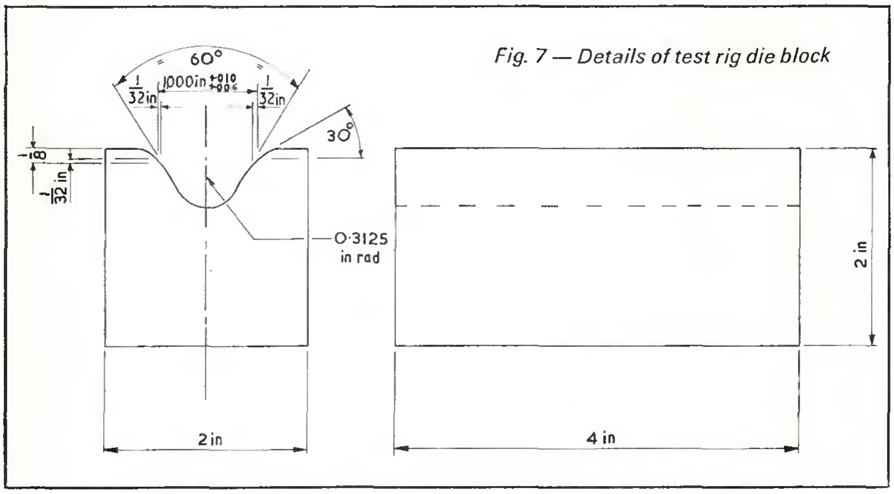

Fig. 7 — Details of test rig die block

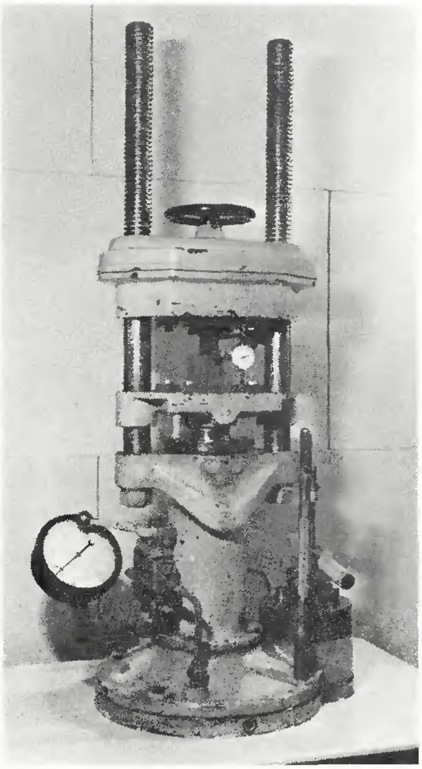

Fig. 8 — Complete test assembly

clearly seen during the slice bend testing of the ten steels. In the case of the ductile steels, where the inclusion content was low, the visual surface failure occurred after the material had undergone a large strain in the thickness direction: this strain was larger than the value to cause 1/8 in. (3.175 mm) cracks in the less ductile steels. Further straining of the ductile steels often produced the required 1/8 in. (3.175 mm) crack. With a further increase of strain, even when the specimen was forced to the bottom of the die block, the crack opened further rather than extending its length.

For steels of lower ductility, which in general had a much higher inclusion content, the visual surface failure occurred after a very small bending deformation and the 1/8 in. (3.175 mm) flaw or crack only a few thousandths of an inch later. The crack was easily propagated in a step-like manner and complete failure across the surface could be produced with small bending deformations, in some cases less than those required to produce visual surface failure in the more ductile materials.

An examination of the results from the slice bend tests carried out on specimens cut from the rolling and transverse directions showed that in the case of the ductile steels a large scatter band was evident, while in the case of the lower ductility steels this band was very much smaller, being often only 0.020 in. (0.508 mm) wide. This may be explained by the fact that the criterion of susceptibility is a 1/8 in. (3.175 mm) crack in the surface of the material: in the case of the ductile steels a 1/8 in. (3.175mm) crack may be formed but there is no propagation of the crack, unlike that in the low ductility steels where the production of the 1/8 in. (3.175 mm) crack was followed immediately by propagation if the strain was further increased. It may be better therefore to consider average values rather than maximum or minimum values of the deformation required to produce the nominal flaw. However, more work would be required to fully establish the point.

When the low ductility and the ductile steels were examined under the optical microscope, it was found in both cases that the cracking was at inclusion sites. To produce the continuous cracking it was therefore necessary to propagate the crack through the matrix material. In order to do this there had to be a low energy path in the matrix material between two existing cracks; this low energy path was produced in some of the steels by the presence of small inclusions between the main crack tips. The mechanism of failure in this case was the formation of multi-axial cracking at these inclusions and the final linking of these cracks to produce final failure; this type of mechanism is clearly shown in Fig. 16.

The examination of the tensile faces of the test pieces after bending deformation, using the scanning electron microscope showed that the presence of the small inclusions was not always required and that fracture could occur where the two crack tips were in close proximity. In this case the mechanism of failure is almost certainly due to the interaction of the two ductile zones at the crack tips, and an example of this type is shown in Fig. 17.

An examination of the fracture surfaces produced by the complete fracture of slice bend specimens revealed considerable information. In the case of the ductile steels the inclusions were often found in clusters or large plates, completely surrounded with fine microvoiding. As the ductility of the material decreased it was noticed that there was a decrease in the amount of microvoiding and the voids containing inclusions became elongated. There was a further feature of the low ductile surfaces in that the lowering of the ductility was accompanied by an increase in the number of shear walls on the surface and also of the steepness of the walls between the test plates.

There was evidence of banding and stringers in some of the steels, this being revealed during the micro-examination of polished specimens from the ten steels. However there was no conclusive evidence as to the effects of these two features on lamellar tearing and further work would be required to prove a correlation or otherwise.

When a comparison was made between the slice bend test specimens, cut in the rolling direction, and the results of the Hounsfield No. 11 tensile test in the thickness direction, it was found that the two tests clearly showed that the least ductile material was 825 steel. At the other end of the scale the Hounsfield tensile test shows 5758 steel was the most ductile. The remaining results showed good correlation between the two tests.

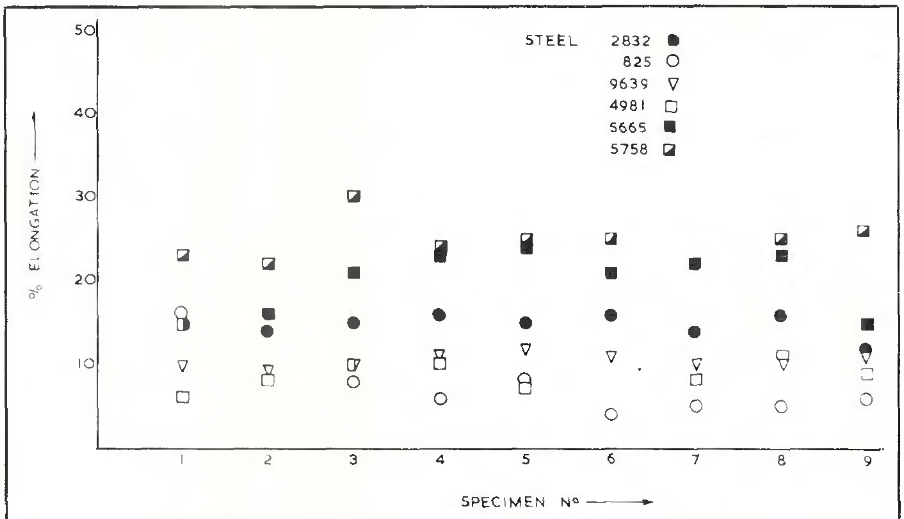

Fig. 9 — Thickness direction tensile test, % elongation

Table 1 — Chemical Analysis of Steels Tested

					Plate number					
Element	M.S.1.	M.S.2.	S.K.1.	F.K.1.	5665	5758	2852	825	4981	9639
Carbon	0.170	0.155	0.140	0.170	0.140	0.160	0.120	0.110	0.160	0.140
Manganese	1.040	0.830	1.230	1.430	0.370	0.390	0.910	0.810	0.930	1.060
Silicon	0.050	0.090	0.600	0.170	0.220	0.260	0.220	0.110	0.230	0.210
Phosphorus	0.031	0.025	0.021	0.027	0.006	0.009	0.012	0.023	0.012	0.016
Sulfur	0.016	0.046	0.034	0.033	0.009	0.009	0.012	0.023	0.028	0.027
Nickel	0.100	0.130	—	—	2.830	2.860	0.990	1.060	1.150	1.080
Chromium	0.070	0.080	—	—	1.500	1.460	0.960	0.700	0.830	0.840
Molybdenum	0.040	0.020	—	—	0.480	0.460	0.460	0.350	0.420	0.400
Vanadium	0.010	0.005	—	—	0.020	0.030	0.070	0.030	0.100	0.060
Arsenic	—	—	—	—	0.023	0.021	—	—	—	—
Titanium	0.010	—	—	—	0.020	—	—	—	—	—
Copper	0.270	0.345	—	—	0.120	—	0.070	—	0.060	—
Aluminum	0.030	—	0.005	0.094	0.020	0.030	0.005	0.010	0.006	0.005
Nitrogen	—	—	0.0045	0.005	0.011	0.009	0.004	0.004	0.002	0.007
Oxygen	—	—	—	—	0.004	—	0.006	—	0.002	0.018

When the slice bend tests, with specimens cut from the transverse direction, were compared with the thickness direction tensile tests, the least ductile steel was still 825 steel according to both tests; the most ductile material according to the tensile test was still 5758 steel and according to the slice bend test 5665 steel. There were discrepancies in the results of the other three steels, but this may have been due to the thickness direction tensile test specimens coming from a different position in the plate.

The inclusion counts that were quoted for the steels could only be used as a guide to susceptibility; this is shown by the fact that steel 825 is less ductile than steels 4891 and 9639, although it has a quoted lower inclusion content. The main reasons that the inclusion counting can only be used as a guide are that the counting is carried out on a very small area and the inclusion population is often randomly spaced in the matrix.

Other workers have already shown that it is not possible to use inclusion counts as a direct measure of susceptibility to lamellar tearing, and this work has shown that this is true. It can however be said that inclusion counts can be helpful initially in roughly sorting the materials. However, much will depend on the method of counting and the magnification at which the counts are made. The argument for inclusion counting is probably stronger for the cleaner steels.

Farrar[1] has suggested from his work that the limits that could be applied to through-thickness tensile tests are:

1. A material showing a reduction in area of less than 20% should be treated as highly susceptible.
2. A material showing a reduction in area of more than 30% can be treated as reasonably satisfactory.

Using the above criteria suggested by Farrar, and applying them to the results obtained from testing the Hounsfield No. 11 tensile specimens of the naval steels, 2832, 825, 4891 and 9639, these steels would all be treated as steels susceptible to lamellar tearing, The remaining two steels would be considered to be resistant. Referring to the slice bend test results on steels 825, 2832, 4891 and 9639, these suggest that where the average deformations are less than 0.100 in. (2.54 mm) to produce a 1/8 in. crack (3.175 mm) these materials should be classed as susceptible to lamellar tearing based on Farrar's criterion.

Table 2 — Thickness of Materials and Inclusion Counts

					Plate number					
	M.S.1.	M.S.2.	S.K.1.	F.K.1.	5665	5758	2832	825	4981	9639
Plate type	BS.15	BS.15	Semi-killed	Fully-killed	Q1 (N)	Q1 (N)	QT35	QT35	QT35	QT35
Plate thickness (in)	1.000	1.000	1.000	1.000	2.000	2.000	1.310	1.230	2.000	2.000
Total sulfide inclusions	—	—	—	—	0.4	1.1	0.8	1.9	3.4	4.6
Total silicate inclusions	—	—	—	—	—	—	1.6	1.8	2.3	3.0
Total alumina inclusions	—	—	—	—	0.3	0.3	—	—	—	—
Total inclusions	—	—	—	—	0.7	1.4	2.4	3.7	5.7	8.6
Tensile strength Tons/sq In.	28.08	30.60	33.68	32.14	43.06	41.99	39.78	42.62	43.65	43.41

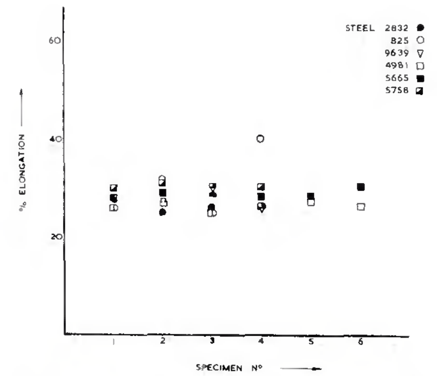

Fig. 10 — Rolling direction tensile test, % elongation

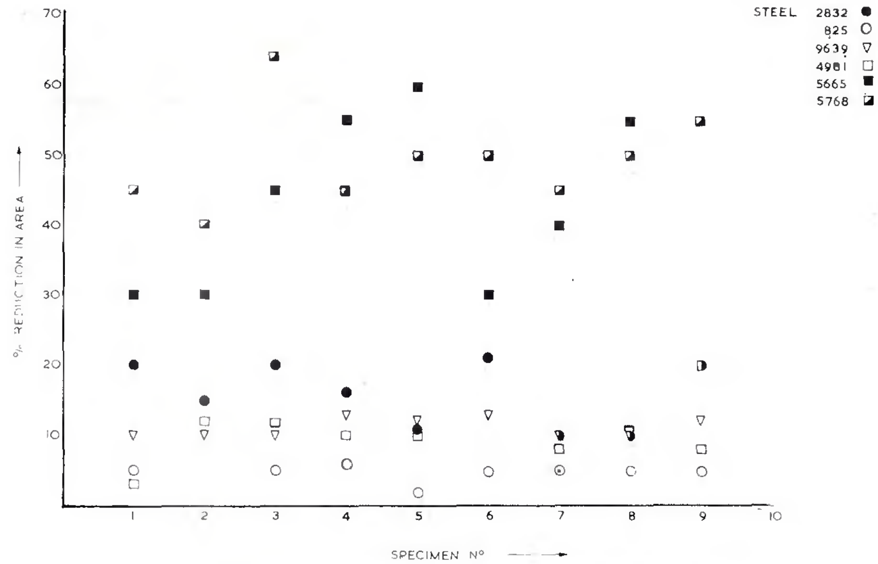

Fig. 11 — Thickness direction tensile test, % reduction in area

The slice bend test showed that if the limits already stated for susceptibility are used, steels F.K.1 and M.S. 2 should be treated as highly susceptible materials, while the S.K. 1 and M.S.1 steels should be treated as satisfactory. The steels however had all been previously weld tested by the Cranfield Crack Test and had shown lamellar tearing, Elliott,[7] Hammond,[8] and Carrick.[9] The findings of the slice bend test would appear to bear out Farrar[10] in his comment that the Cranfield Crack Test is a severe test and will produce cracking in many steels, some of which are not susceptible to lamellar tearing in most fabrications. Further testing will therefore be necessary to establish the relationship between weld tests and the slice bend test.

From the slice bend tests already carried out it appears that the tolerances that have been applied to the thickness of the specimens could possibly be relaxed, and a more general tolerance applied. It would however seem at the present stage of investigation of the test that the practice of grinding the specimens and also the maintaining of the grinding marks at 45 deg to the testing axis should be continued.

The fracture surfaces containing shear walls were compared with fracture surfaces of other workers, particularly those of Elliott.[7] It was found that the features were comparable and that if the features that are produced by welding tests are taken as being representative of those found in fabrication failures, then those produced by the slice bend test will give a further indication of a steel's susceptibility to lamellar tearing.

If the slice bend test is appraised overall it appears to be a test in which the specimens can be produced using normal machining capacity, and be ground in the final stages in quantities of up to twelve at a time, thus saving on the machining time. The testing equipment necessary is simple, requiring little capital outlay, etc.

The testing of the specimens is simple and easy, requiring only limited skill on the part of the operator. The interpretation of the results again is not difficult, and with a small amount of instruction relatively unskilled labor could carry out the test and interpret the results quite easily.

Therefore it may be said that the slice bend test is a destructive test that may be easily produced, tested and interpreted, providing a destructive means of sorting steels for susceptibility to lamellar tearing. It also provides a means by which the mechanism of lamellar tearing initiation and propagation may be studied.

This program of tests, to which the following conclusions apply, was carried out on steels with tensile strengths in the range 28 to 44 tons/sq. in.

Conclusions

1. The slice bend test is one which can be carried out using simple and inexpensive equipment.
2. The specimens for slice bend testing can be prepared using basic equipment of the saw and surface grinder.
3. The testing and interpretation of the results can be carried out by a relatively unskilled worker. With more research it is possible that the interpretation could be further simplified.
4. A criterion for the test, to sort the materials according to ductility, is the amount of deformation required to produce a 1/8 in. (3.175 mm) crack in the tension face of the bend specimen.

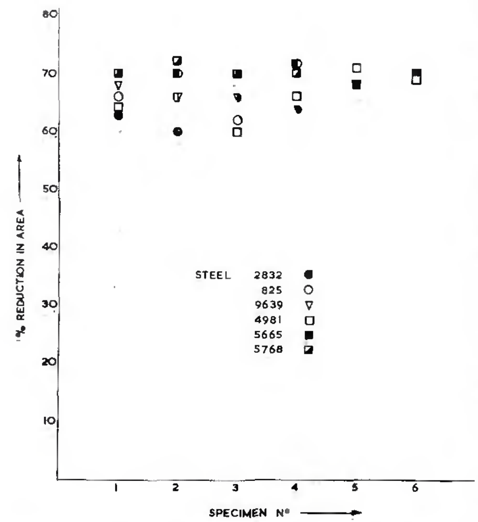

Fig. 12 — Rolling direction tensile test, % reduction in area

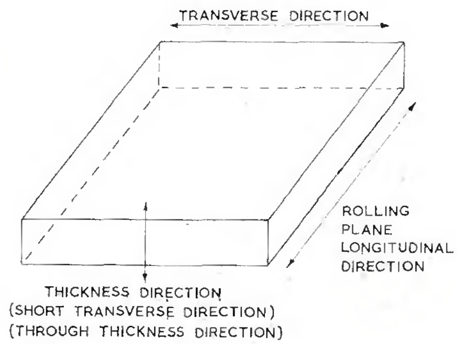

Fig. 13 — Sketch of plate directions

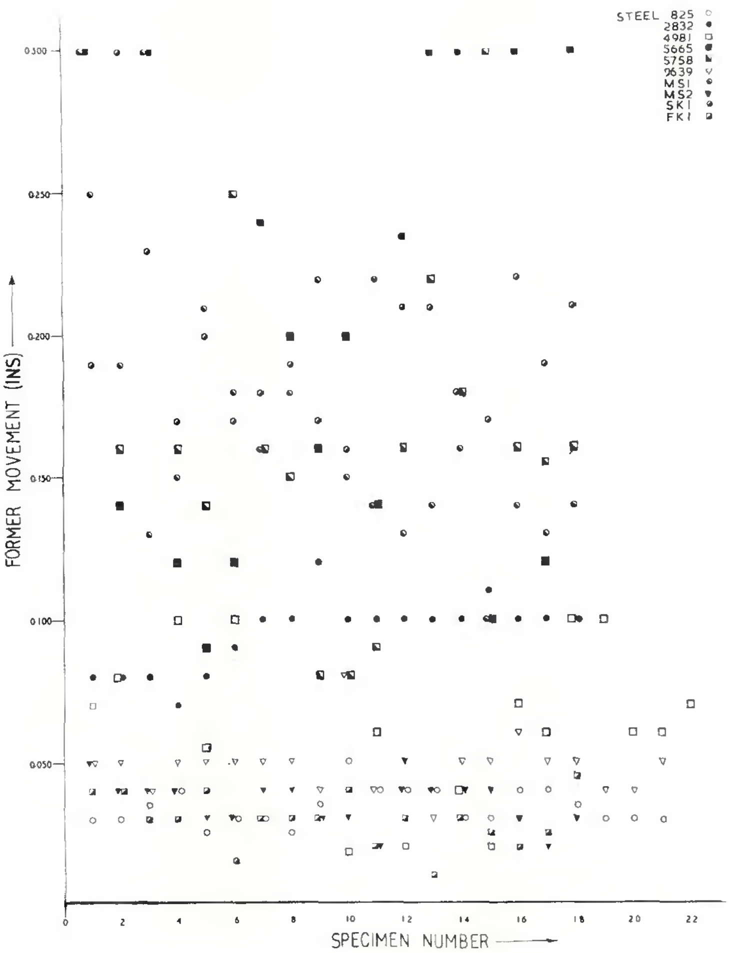

Fig. 14 — Results of slice bend tests, rolling direction

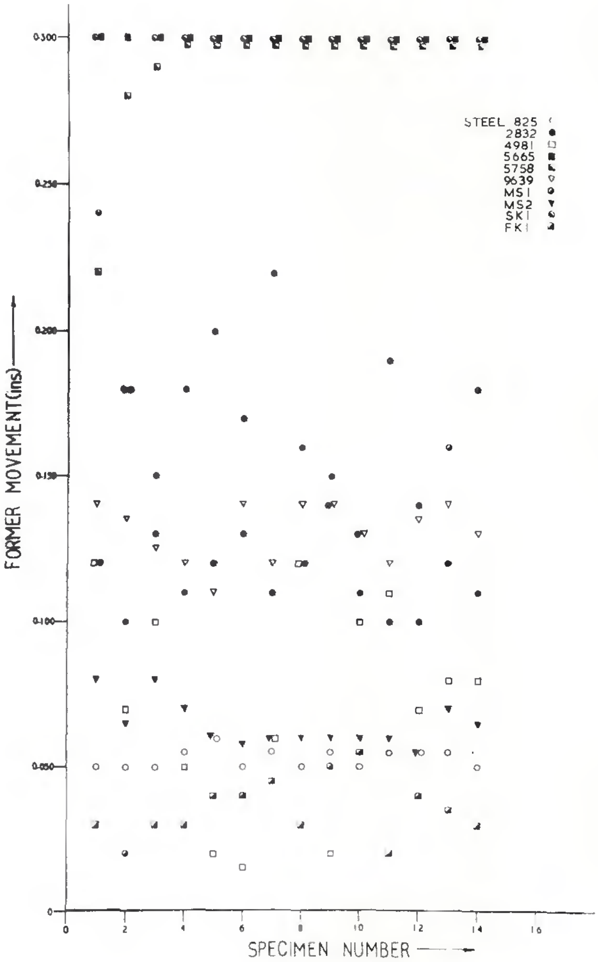

Fig. 15 — Results of slice bend tests, transverse direction

5. The slice bend test shows good correlation with the Hounsfield No. 11 tensile test in the thickness direction, and it is cheaper to make the test.

6. The slice bend test is statistically more representative of the material under test than the tensile test; it is less affected by the random inclusion population.

7. The fracture surfaces from slice bend tests have the characteristic fractographical features associated with the surfaces of lamellar tears, where the material under test is susceptible to lamellar tearing.

8. The slice bend test can produce fracture surfaces which may be examined and compared with the fracture surfaces of materials with a known history of this type of failure.

9. The slice bend test is suitable for the sorting of materials, in an unwelded state, for susceptibility to lamellar tearing.

10. The appearance of the tension surface of the slice bend test gives a good indication of material's susceptibility to lamellar tearing. Where linking between initial cracks is very marked for small deformations susceptibility to lamellar tearing is high.

11. Existing evidence from this program of tests used in conjunction with criteria suggested by Farrar on the susceptibility of materials to lamellar tearing, indicates that the slice bend test can be applied to welding fabrications as follows:

a) where a flaw of 1/8 in. (3.175 mm) is produced with an average deformation of less than 0.100 in. (2.54 mm) then the materials may be regarded as highly susceptible to lamellar tearing when testing specimens cut from the rolling direction.

b) where the average deformation required to produce an 1/8 in. (3.175 mm) flaw is greater than 0.150 in. (3.81 mm) the material may be regarded as having resistance to lamellar tearing.

12. The slice bend test and the through thickness tensile test are relevant to material in the middle region of the specimen.

Acknowledgements

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Their special thanks are extended to Mr. A. D. E. Thomson, Mr. J. Bird and the staff of the Naval Construction Research Establishment, Dunfermline, for the supply of material for investigation, the inclusion counts, chemical analyses, and useful comments in the early stages.

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Grateful thanks are also extended to the Cranfield Institute of Technology for permission to use and publish the findings. To the Academic and Technical staff of the Departments of Aircraft Design and Materials gratitude is extended for their help and comments.

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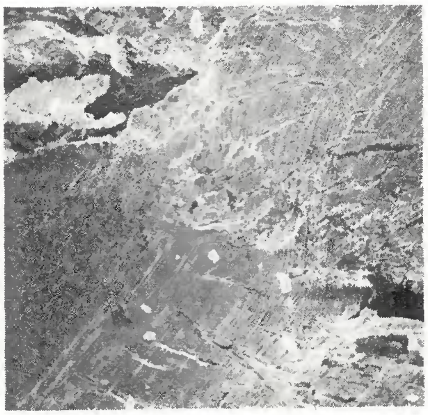

Fig. 16 — Multiaxial cracking between inclusion voids on tension face of a slice bend specimen (X200, reduced 54%)

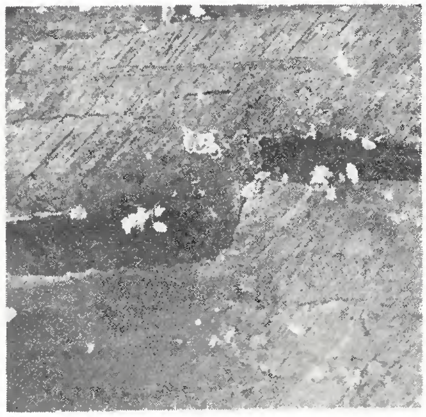

Fig. 17 — Shear crack between the tips of inclusion voids on tension face of a slice bend specimen (X200, reduced 54%)

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"Joining Ceramics and Other Materials"

By H. E. Pattee

The technology of joining ceramics to metals has progressed steadily since its beginnings in the late 1930's. Like other joining processes, the joining of ceramics to themselves and to other materials was long considered to be more an art than a science. Because of extensive research efforts directed to the development of procedures for producing reliable ceramic-to-metal joints, much has been accomplished in the intervening years to establish a joining technology based on sound fundamental procedures and an understanding of the reactions that occur during joining.

This report discusses the joining of bulk ceramics to metals and other materials. Ceramic-to-metal joining as applied in the electronics industry is emphasized, because more research has been initiated by this industry than by any other. As a result, an extensive background of information is available. However, the techniques developed to produce ceramic-to-metal seals and joints for electronic devices can frequently be used for other applications.

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Local Stresses in Spherical and Cylindrical Shells Due to External Loadings

by K. R. Wichman, A. G. Hopper and J. L. Mershon

Several years ago, the Pressure Vessel Research Committee sponsored an analytical and experimental research program aimed at providing methods of determining the stresses in pressure vessel nozzle connections subjected to various forms of external loading. The analytical portion of this work was accomplished by Prof. P. P. Bijlaard of Cornell University. Development of the theoretical solutions involved a number of simplifying assumptions, including the use of shallow shell theory for spherical vessels and flexible loading surfaces for cylindrical vessels. These circumstances limited the potential usefulness of the results to d_i/D_i ratios of perhaps 0.33 in the case of spherical shells and 0.25 in the case of cylindrical shells. Since no data were available for the larger diameter ratios, Prof. Bijlaard later supplied data, at the urging of the design engineers, for the values of $B = 0.375$ and 0.50 (d_i/D_i ratios approaching 0.60) for cylindrical shells. In so doing, Prof. Bijlaard included a specific warning concerning the possible limitations of these data.

Following completion of the theoretical work, experimental work was undertaken in an effort to verify the theory. Whereas this work seemingly provided reasonable verification of the theory, it was limited to relatively small d_i/D_i ratios—0.10 in the case of spherical shells and 0.126 in the case of cylindrical shells. Since virtually no data, either analytical or experimental, were available covering the larger diameter ratios, the Bureau of Ships sponsored a limited investigation of this problem in spheres, aimed at a particular design problem, and the Pressure Vessel Research Committee undertook a somewhat similar investigation in cylinders. Results of this work emphasized the limitations in Bijlaard's data on cylindrical shells, particularly as it applies to thin shells over the "extended range."

Incident to the use of Bijlaard's data for design purposes, it had become apparent that design engineers sometimes have difficulty in interpreting or properly applying this work. As a result of such experience, PVRC felt it desirable that all of Bijlaard's work be summarized in convenient, "cookbook" form to facilitate its use by design engineers. However, before this document could be issued, the above mentioned limitations became apparent presenting an unfortunate dilemma, viz., the data indicate that the data are partially inadequate, but the exact nature and magnitude of the error is not known, nor is any better analytical treatment of the problem available (for cylinders).

Under these circumstances, it was decided that the best course was to proceed with issuing the "cookbook," extending Bijlaard's curves as best as possible on the basis of available test data. This decision was based on the premise that all of the proposed changes would be toward the conservative (or "safe") side and that design engineers would continue to use Bijlaard's extended range data unless some alternative were offered. This paper was therefore presented in the hope that it would facilitate the use of Bijlaard's work by design engineers.

Since the paper was originally issued, a number of minor errors have been discovered and incorporated in revised printings as supplies were exhausted. The third revised printing was issued in April 1972.

The price of Bulletin No. 107 is $3.00. Single copies may be ordered from the American Welding Society, 2501 N.W. 7th St., Miami, Fla. 33125. Bulk lots may be ordered from the Welding Research Council, 345 East 47th St., New York, N. Y. 10017.