Prediction of Lamellar Tearing Susceptibility by Mechanical Testing

An easily used, inexpensive mechanical testing procedure may be used to predict resistance to lamellar tearing

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ABSTRACT. The susceptibility of a material to lamellar tearing during welding has been related to the ability of the material to withstand through-thickness stresses. In situations where detrimental through-thickness stresses cannot be reduced by changes in joint design and/or welding practice, the ductility of the material in the through-thickness direction becomes extremely important.

To assess the resistance of a material to lamellar tearing, several types of mechanical tests have been proposed. The short transverse tension test, bend test, ring test and notched impact test are utilized to examine base metal ductility or toughness. In each of these tests, the material tested is generally machined from regions close to the plate surface without utilizing welded end tabs.

The Lehigh lamellar tear test is also used to assess resistance to lamellar tearing. At present, the Lehigh lamellar tear test is probably the best test, because it combines the material properties with a welding procedure to determine a critical weld restraint level. This test is, however, cumbersome to perform and requires considerable material. What is needed is a test parameter which can be determined from simple mechanical tests and which correlates with the accepted Lehigh lamellar tear test.

Longitudinal compression tests and through-thickness tensile tests were performed on several plates and these results were correlated with the results of Lehigh lamellar tear tests which were performed on identical plates. A simple parameter to define the resistance of a material to lamellar tearing is proposed as follows:

\[ RLT = \frac{\epsilon_y}{\sigma} \]

where RLT is the resistance to lamellar tearing; \( \epsilon_y \) is the plane strain intercept of the through-thickness fracture line determined by longitudinal compression testing; and \( \sigma \) is the tensile strength in the through-thickness direction. High values of RLT indicate an inherently low susceptibility to lamellar tearing.

Lamellar tearing can be described as a two-step process. First, a through-thickness stress causes voids to form either by delamination at inclusion/matrix interfaces or by inclusion cracking. Second, these voids are joined by cracks which propagate along bands of intense shear which form between voids. Resistance to lamellar tearing can thus be thought of as resistance to void formation (high ultimate strength) and/or resistance to cracking (high ductility). The proposed RLT parameter considers both of these two factors.

Excellent correlations were obtained between the RLT parameter and Lehigh lamellar tear test results, indicating that an easy, inexpensive mechanical testing procedure can be used to predict resistance to lamellar tearing.

Introduction

Lamellar tearing is a form of cracking in welded constructional material which is due to a combination of the anisotropic character of hot rolled plate together with high weld stresses in which the plate is stressed normal to its rolling plane. The cracks have a step-like appearance and are presumed to be associated with inclusions oriented along the rolling plane.

Lamellar Tearing Theory

A universal theory of lamellar tearing has been proposed which explains the characteristic appearance and behavior of a lamellar tear. In the initial stages of crack formation, the application of stress or strain normal to inclusions or groups of inclusions promotes inclusion fracture or inclusion-matrix decohesion. The case of this decohesion is enhanced when the inclusions are aligned in groups along the rolling planes. Furthermore, it can be argued that thin lamellar inclusions associated with rolling are expected to delaminate more easily than round globular ones. Finally, an effect of inclusion type is expected. Those inclusions which have stronger cohesive interaction forces with the matrix and greater inherent ductility would be less affected by localized straining than those with weaker inclusion-matrix interactions and less ductility.

Considerable debate has occurred about the exact nature and type of second phase particles which are most susceptible. It is generally agreed that the particles which are most troublesome are manganese and aluminum silicates. These occur as a result of the deoxidation practices and are elongated during subsequent processing.

Manganese sulfide particles are also...
The second stage of lamellar tearing consists of the linking up of these voids. This implies that a certain amount of plastic deformation occurs within the triaxially stressed regions ahead of each of the voids. This being the case, one can assume that the physical properties of the matrix material, itself, should exhibit some effect upon microvoid link up and overall crack growth. When these voids link up with voids on the same or parallel planes (depending on whichever route offers the least resistance), crack propagation with the characteristic stepped appearance occurs.

Certainly, factors which affect the resistance to crack growth are matrix strength and ductility. A decrease in the intrinsic matrix ductility for a material of given strength and inclusion population would be expected to increase the susceptibility to lamellar tearing. Similarly, a decrease in the lattice cohesion in the triaxially stressed region ahead of the microvoids also increases susceptibility.

In summary then, the following conditions can be listed as contributing factors to lamellar tearing in welds:

1. The application of a stress or strain in the direction normal to the plane of a plate. These are most commonly due to welding stresses.
2. The occurrence of second phase particles of aluminum or manganese silicate or manganese sulfides located within planes parallel to the plane of the plate.
3. Matrix conditions which promote easy link up of the voids caused by second phase particle decohesion.

Precautionary Welding Measures

In line with the foregoing discussion, several precautionary measures can be taken during welding in order to minimize the occurrence of lamellar tearing. However, the basic mechanisms of lamellar tearing are related to metallurgical properties of the steel itself. Because of this, it should be stressed that these measures only minimize the occurrence of tearing and neither eliminate nor remove the inherent susceptibility of the material for lamellar tearing.

Since the localized strains around a welded joint are related to lamellar tearing, methods which reduce the overall strain experienced within the susceptible region will reduce tearing. Several methods for achieving this are indicated in this paper. The first and probably most effective is to redesign critical joint geometries—this is, to design joints where the maximum value of strain acts in some direction other than normal to the rolling plane of the plate. This is not as difficult as it first sounds since a change in the preweld groove design can usually be found in which the welding strains are shared between the base metal and the welded part.

A second method of reducing the strain within the susceptible region is through the use of weld metal having strength less than and ductility greater than that of the base metal. Therefore, any straining which occurs due to the welding process will be taken up in the form of weld metal deformation reducing strains elsewhere.

A related procedure called “buttering” can also be used. This consists of applying a layer of lower strength, high ductility, weld metal as the initial passes. Again, any straining due to subsequent welding passes is reduced by localized yielding of the “buttered” pass.

Proper selection of the weld pass sequence can also be effective in reducing the buildup of stresses in localized areas. In this procedure, weld placement is controlled so that stresses produced by the first weld pass are counteracted in part by the subsequent passes. This helps to reduce high stresses ahead of the weld due to bending moments. Such a procedure is called balanced welding.

In some cases, the use of preheat has also been shown to reduce the overall strains within susceptible metal after cooling from welding. The effect of preheat, however, appears to depend upon plate size and type of structure and thus may be a function of low temperature transformation properties.

Varied recommendations have also been made about control of welding variables to reduce the extent of lamellar tearing. Some indicate that high heat and deep penetration are effective, while others indicate that electrode manipulation with a wide weave bead is advantageous.

Finally, the selection of clean steels or steels which have some inclusion treatments for control of particle size, distribution, and shape cannot be overstressed. It is felt that the selection of steels on the basis of microstructure and second phase morphology can significantly reduce susceptibility.

Susceptibility Tests

As mentioned previously, the susceptibility to lamellar tearing is related to metallurgical characteristics of the steel itself and, as such, the development of a test for steel susceptibility is mandatory. These tests can generally be divided into two types, i.e., those not using a welding procedure as part of the test, and those using a weld procedure as part of the test.

Of the unwelded tests, the most popular are: short transverse tensile testing, bend testing, ring testing, and notched impact testing. Values obtained from short transverse tensile testing, however, are often not indicative of actual weldments.
Tests have been used to select plates with acceptable through-thickness ductility. Unfortunately, correlations which relate ductility to lamellar tearing are limited. Furthermore, the material tested is generally machined from the central region of the plate whereas lamellar tearing is often observed in material closer to the surface. Several modifications and variations of bend tests have been developed. In general, samples which are cut from the through-thickness direction of a plate and either notched or unnotched are bent through various radii. The occurrence of cracks is in some measure related to susceptibility. However, correlations are difficult because of sampling techniques and the locations of susceptible areas being remote from the bond sample center location.

In the ring test, rings are cut from the through-thickness direction of a plate. The ring is then loaded and supported so that a varying moment occurs around the ring. The occurrence and location of cracks relate to the susceptibility. Again, this test suffers from the same difficulties as the above mentioned tests. Typical Charpy V-notch specimens cut from the thickness direction of the plate have been used. It is difficult to rationalize a relationship between Charpy failures and lamellar tearing susceptibility because of the large differences in fracture rate. However, the method has had some reasonable correlation success. It is felt that this test should be used with caution, however, and only to demonstrate plate anisotropy.

Of the welded tests, the most popular are the Cranfield test, the window test, and the Lehigh lamellar tear test. The Cranfield welding test illustrated in Fig. 1 consists of welding a support plate at a 45 or 60 deg angle to a test plate. The shrinkage strains associated with the multirun welding procedure are used to achieve a variable amount of strain normal to the test plate. The occurrence of under bead cracking is taken as a discrimination between acceptable and unacceptable material.

In the window test, illustrated in Fig. 2, a test plate is inserted through a square hole "V" grooved window in a restraining block and is welded in place with four single pass welds. The restraint caused by these welds promotes tearing within the test plate. The occurrence and severity of the tearing is taken as a measure of lamellar tear susceptibility.

These two tests suffer from uncertainty of the exact stress and strain applied to the test material. Furthermore, results obtained with these tests are only semi-quantitative at best. On the other hand, the Lehigh lamellar tear test, illustrated in Fig. 3, consists of welding a cantilever beam to a test plate. The restraint level within the weld and the heat-affected zone is maintained at a predetermined level by adjusting the load on the cantilever beam after each weld pass. The load applied is calculated to exactly produce a desired restraint level and thus takes factors like the load lever arm length, the weld thickness, and the size of the test piece into consideration. The occurrence of lamellar tears is correlated with the amount of this external restraint. The particular restraint level at which lamellar tearing just occurs is called the "critical weld restraint level" (CWRX) for the material in question. The relative susceptibility of various materials to lamellar tearing then is simply represented by the relative values of the critical weld restraint level.

The Lehigh lamellar tear test offers many advantages over all of the other tests. These advantages include the ability to independently vary weld restraint, the use of actual welding thermal cycles, the ease of interpretation, and the testing of material near the plate surface (rather than at the mid-plane) where lamellar tearing actually occurs. The major disadvantage of this test, however, is that it requires large amounts of test material and requires considerable effort to perform the test.

**Purpose of Experimental Project**

One purpose of this experimental project was to examine relatively simple mechanical tests (such as longitudinal compression tests and through-thickness tensile tests) as a method of evaluating lamellar tear susceptibility of plate material; another was to correlate the results from these tests with those from Lehigh lamellar tear testing.

An additional purpose was to develop a test parameter which more accurately defines the resistance of a material to lamellar tearing. This factor should consider both strength and ductility properties since the lamellar tear is related to both the strength and

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**Table 1—Chemistry of Materials Investigated, %**

<table>
<thead>
<tr>
<th>Alloy type</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
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<th>Cr</th>
<th>Mo</th>
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<td>0.42</td>
<td>0.20</td>
<td>0.011</td>
<td>0.025</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1020 Al-killed</td>
<td>0.23</td>
<td>0.56</td>
<td>0.027</td>
<td>0.010</td>
<td>0.012</td>
<td>–</td>
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<td>–</td>
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<tr>
<td>X42</td>
<td>0.21</td>
<td>0.90</td>
<td>0.06</td>
<td>0.013</td>
<td>0.002</td>
<td>0.06</td>
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<td>&lt;0.01</td>
<td>0.01</td>
<td>0.601</td>
</tr>
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<td>0.16</td>
<td>1.01</td>
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<td>0.013</td>
<td>0.010</td>
<td>0.73</td>
<td>1.42</td>
<td>1.16</td>
<td>0.36</td>
<td>0.05</td>
<td>0.03</td>
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ductility of the material as discussed earlier.

Materials and Procedures

Four materials were investigated. Two 1020-type plate materials (one silicon killed and one aluminum killed) were tested. These plates represent a low-strength product with yield strengths approximately equal to 30 ksi (207 MPa). The third plate tested was an X42 material. This semi-killed material was intermediate in strength and had a yield strength of about 45 ksi (310 MPa). The fourth plate was a high-strength as-rolled abrasion-resistant plate with 100 ksi (689 MPa) yield strength (REPUBLIC 100-AR*). The 100-AR material was aluminum killed with rare earth sulfide shape control.

These four plates were selected to give a wide range of nominal strength level, as well as variations in killing practice and sulfide shape control. The chemistries of these plate products are presented in Table 1.

Lehigh lamellar tear tests were conducted on each material. Details of the procedure are specified elsewhere. Briefly, the test consists of welding a cantilever plate which is statically loaded during welding to a test plate. After each weld has cooled to below 200°F (93°C), the load is readjusted to maintain the desired stress (a loss occurs due to deformation occurring in the hot weld metal during each pass). This sequence is repeated until either the bevel groove is completely filled or test plate failure occurs.

Duplicate tests are conducted with varying weld restraint levels until a restraint level is identified at which lamellar tearing occurs. This is called the critical weld restraint level.

Short transverse tensile samples and in-plane (longitudinal) compression slugs were also sectioned from each plate as indicated in Fig. 5. The tensile samples were 0.5 in. (12.7 mm) gage length, 0.252 in. (6.4 mm) diameter test samples. The compression slugs were machined to two different diameters and heights (0.5 in. (12.7 mm) diameter by 0.75 in. (19.1 mm) height and 0.5 in. (12.7 mm) diameter by 1.0 in. (25.4 mm) height; making height/diameter ratios of 1.5 and 2.0, respectively).

In compression testing, the slugs were loaded between flat dies using Al2O3 grit to hold end friction constant. After each load increment of 15,000 pounds (6,804 kg), the slug was removed from the die set and visually examined for surface cracking. The test was completed when fracture was observed. Data obtained were height, diameter, and load at fracture.

Compression Testing

Before considering the results, a description of the compression test method is required. In the compression test, a cylinder of initial height H₀ and diameter D₀ is compressed to the point of fracture. As indicated in Fig. 6, the free surface of the cylinder bulges due to end friction during compression. Failure occurs by tearing near mid-height (Fig. 5).

The strains during deformation can
be determined by considering a reference grid at mid-height with an initial height of \( h_0 \) and radial diameter of \( d_0 \). During compression, the height and radial diameter deform as indicated in Fig. 6, with the instantaneous height and diameter being represented by \( h \) and \( d \), respectively. The local height or axial strain can be calculated by the formula:

\[
\varepsilon_a = \ln \frac{h}{h_0}
\]

and the local circumferential strain can be calculated by the formula:

\[
\varepsilon_c = \ln \frac{d}{d_0}
\]

The strain path (i.e., the variation in axial and circumferential strain) during testing is represented in Fig. 7. The strain path followed is dictated by the specimen geometry (height/diameter ratio) and the friction conditions present between the dies and the deforming cylinder.

Various strain paths to fracture for a high and low friction condition and for \( H_o/D_o \) ratios of 0.75 and 1.0 are illustrated in Fig. 7. These strain paths terminate at the point of fracture. Note that the locus of fracture points for a given material fall on a straight line with a slope of \( \frac{1}{2} \), irrespective of the strain path taken to fracture. This fracture condition will shift vertically for materials (as indicated in Fig. 7), but in all cases the slope of \( \frac{1}{2} \) will be maintained. Thus, the fracture locus (i.e., fracture condition line) can serve to rank materials.

Since the circumferential and axial strain values at fracture can vary depending upon strain path along the fracture condition line, these values by themselves do not define the fracture condition line. However, since the slope of this line is identical for all materials, the \( y \)-axis intercept value can be used to define the fracture condition line for each material. This value (the plain strain intercept) is represented by \( \varepsilon_{p}^{s} \) in Fig. 7.

**Results**

The results of Lehigh lamellar tear testing (LLTT) are presented in Table 2. The plate materials are ranked in order of their susceptibility as judged by this test with the 1020 silicon killed material being the most susceptible (i.e., failed at the lowest weld restraint levels) and the 100-AR material being the least susceptible.

The results of the short transverse tensile testing are also listed in Table 2. It should be noted that the value of percent elongation or percent reduction in area, as conventionally used, underestimates the performance of the high-strength 100-AR.

The strain at fracture in the compression tests was determined for each material. Both axial and circumferential fracture strains were determined for samples with \( H_o/D_o \) ratios of 1.5 and 2.0. The values of fracture strains (fracture condition points) were plotted simultaneously, as illustrated in Fig. 8 for both the 100-AR plate and the X42 plate. A line with a slope of \( \frac{1}{2} \) was constructed through the fracture condition points for each material and the plain strain intercept (\( \varepsilon_{p}^{s} \)) was determined for each line. Values for all four materials of the plain strain intercept determined from compression testing are presented in Table 2.

**Discussion**

The formation of a lamellar tear has been described as a two-step process. First, a through-thickness stress causes voids to form either by delamination at inclusion/matrix interfaces or by inclusion cracking. Second, these voids are joined by cracks which propagate along bands of intense shear which form between voids.

The net effect is a fracture surface that is characterized as a series of terraces (inclusion-related areas) and steps (matrix-related areas). This means that both inclusions and the matrix are important in determining the susceptibility of a material to lamellar tearing. Inclusions are a very significant factor in determining a material’s fracture strain, while the

<table>
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<th>Alloy type</th>
<th>Lehigh critical weld restraint, kpsi</th>
<th>Short Transverse Tensile Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1020 Si-killed</td>
<td>50</td>
<td>Yield strength, ksi</td>
</tr>
<tr>
<td>1020 Al-killed</td>
<td>70</td>
<td>26.4</td>
</tr>
<tr>
<td>X42</td>
<td>85</td>
<td>37.1</td>
</tr>
<tr>
<td>100-AR</td>
<td>&gt; 100</td>
<td>97.5</td>
</tr>
</tbody>
</table>
matrix controls the strength and plasticity. Therefore, both material ductility and strength factors must be considered to give accurate lamellar tear susceptibility prediction. Most of the non-welded mechanical tests previously used and described in the introduction depend on ductility values only for prediction capability. Figure 9 shows the relationship between the critical weld restraint levels for the tested materials and the ductility-related term (i.e., the plain strain intercept). As noted, the simple ductility-related term was only moderately successful for prediction.

A new parameter to define the resistance of a material to lamellar tearing which includes both strength and ductility terms is proposed as follows:

$$RLT = \epsilon_0 \cdot \alpha,$$

where RLT is the resistance to lamellar tearing, \(\epsilon_0\) is the plain strain intercept of the through-thickness fracture line determined by longitudinal compression testing, and \(\alpha\) is the tensile strength in the through-thickness direction. Tensile strength is chosen because it marks a point of plastic instability. High values of RLT indicate an inherently low susceptibility to lamellar tearing.

A plot of the parameter RLT vs. the CWRL values determined from the Lehigh lamellar tear test is shown in Fig. 10. Based on these data, the parameter behaves properly in that both the RLT values and the CWRL values increase simultaneously. According to the RLT parameter, resistance to lamellar tearing can be gained by having either a high through-thickness ductility (e.g., X42) or high through-thickness strength (e.g., 100-Ar), or both.

The 1020 steels plotted in Fig. 10 illustrate the effect of ductility. Both have similar strength levels, but the aluminum killed steel has higher ductility than the silicon killed steel and thus has higher RLT and CWRL values. Based on the positions of the steels on the line in Fig. 10, 100-Ar has the highest resistance to lamellar tearing and 1020 silicon killed the lowest. It should be remembered, however, that the application of these steels is different so that such a statement only applies to the inherent or material-based resistance to lamellar tearing. In practice, the joint geometry and welding practice must also be considered.

**Conclusion**

The results of both the longitudinal compression test and the through-thickness tension test indicate that ductility values alone may not be sufficient to describe the lamellar tear susceptibility of a material. The limitation of the ductility parameter establishes a need for a parameter which combines strength and ductility. Thus, a new parameter (RLT) is defined to determine resistance to lamellar tearing, such that:

$$RLT = \epsilon_0 \cdot \alpha,$$

where \(\epsilon_0\) is the plane strain intercept of the longitudinal compression fracture line (through-thickness ductility term which is inclusion-related) and \(\alpha\) is the through-thickness tensile strength (matrix-related term). This parameter correlates well with the CWRL values for the materials tested.

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**References**


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