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Assessment of Lamellar Tearing

J. W. McEnemey

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J. W. McEnerney

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CONTENTS

ABSTRACT	1
INTRODUCTION	2
DESCRIPTION	3
MATERIAL VARIABLES	7
WELDING VARIABLES	12
DESIGN VARIABLES	15
TESTS FOR ASSESSING MATERIAL SUSCEPTIBILITY	18
Tests Without Simulated or Actual Welding Cycle	19
Tests With Simulated Temperature and Strain Cycles	28
Tests With Temperature and Strain Cycle by Welding	29
Tests of a Prototypic Welded Joint	34
DETECTION AND REPAIR OF LAMELLAR TEARS AFTER WELDING	34
SIGNIFICANCE OF SERVICE LOADING OF MATERIAL SUSCEPTIBLE TO LAMELLAR TEARING	36
RECOMMENDATIONS FOR AVOIDING LAMELLAR TEARING DURING FABRICATION OR SERVICE LOADING	41
ASSESSMENT OF ASME CODE REQUIREMENTS	45
CONCLUSIONS	49
ACKNOWLEDGMENTS	50
REFERENCES	50

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ABSTRACT

Information on lamellar tearing is summarized and related to proposed ASME Code requirements.

Lamellar tearing is characterized as a complex phenomenon related to poor short transverse ductility and through-thickness strain. Although nonmetallic inclusions play a dominant role in lowering the ductility, steel matrix properties are also important. The through-thickness strain is generally caused by localized weld thermal contractions, but could result from certain service loads. The material, welding, and design variables that affect lamellar tearing are shown to be complex and interrelated.

The commonly reported tests for assessing material susceptibility are described, with the controversy over their validity being carefully detailed. Although the use of a nondestructive test such as ultrasonic examination is most desirable, a widely applicable test method does not appear to be available. Of the destructive tests, the short transverse tensile reduction-of-area currently offers the most applicable means of assessing material susceptibility. However, because of the importance of matrix toughness, the short transverse Charpy V-notch test should be considered for use as an additional test if acceptance limits are developed.

The ultrasonic detection of lamellar tears is susceptible to interpretation errors, which can make it overly conservative and lead to unnecessary repairs. The repair of tears is described as costly, difficult, and sometimes ineffective.

Current ASME Code Section III, Division 1, Subsection NF design requirements appear to preclude any failures during static and fatigue service loads. However, without improvement of short transverse ductility, certain dynamic service loads could cause lamellar tearing failures. Two alternate design paths are recommended to prevent tearing during fabrication or service loading. The more desirable path improves short transverse ductility while the other relies on ultrasonic examination of finished welds or buttering. The current and proposed ASME Code Section III, Division 1, Subsection NF requirements dealing with lamellar tearing are reviewed and recommendations are made.

INTRODUCTION

Incidents of lamellar tearing have been reported in most heavy fabrication industries, such as shipbuilding, nuclear and fossil power plant erection, bridge and building construction, production of off-shore structures, and conventional pressure vessel fabrication. These incidents are normally associated with the welding of hot-rolled carbon and low-alloy steel plates and shapes made by conventional steelmaking practices (CON). Table 1 lists some typical American and British steel specifications with reported^{1,2} histories of lamellar tearing. Because of the widespread occurrence, a considerable amount of research has been devoted to investigating the phenomenon. However, despite this research effort, there is still disagreement concerning various aspects of the lamellar tearing problem.

Table 1. Typical American and British Steel Specifications with Reported^a Histories of Lamellar Tearing

Specification	Description	Normal Deoxidation Practice
<u>British Specifications</u>		
B. S. 1501-151	Structural Carbon Steel	Semi Killed
B. S. 1501-161	Structural Carbon Steel	Fully Si-Killed
B. S. 1501-224	Grain Refined Structural Carbon Steel	Fully Si-Killed plus Al
B. S. 4360-43	Structural Carbon Steel	Semi Killed
Lloyds E Grade	Grain Refined Structural Carbon Steel	Fully Si-Killed plus Al
Admiralty "B"	Grain Refined Structural Carbon Steel	Fully Si-Killed plus Al
<u>American Specifications</u>		
SA-, A 36	Structural Carbon Steel	Semi Killed
SA-, A 283	Structural Carbon Steel	Si-Killed
SA-, A 285	Pressure Vessel Carbon Steel	Semi Killed
SA-, A 515	Pressure Vessel Carbon Steel	Si-Killed
SA-, A 516	Grain Refined Pressure Vessel Carbon Steel	Fully Si-Killed plus Al

^aJ.C.M. Farrar and R. E. Dolby, "Lamellar Tearing in Welded Steel Fabrication," Phase I of *Investigations into Lamellar Tearing. A Compendium of Reports from a Sponsored Research Programme*, Welding Institute, Cambridge, England, March 1975; S. Ganesh and R. D. Stout, "Material Variables Affecting Lamellar Tearing Susceptibility in Steels," *Weld. J. (Miami)* 55(11): 341-s-354-s (November 1976).

An ASME Code committee task group has been considering the problem of lamellar tearing for several years. They are currently formulating requirements for ASME Code Section III, Division 1, Subsection NF component support applications. The intent of this report is to summarize the available information on lamellar tearing and then examine its significance and the effectiveness of the proposed ASME Code III-NF requirements.

DESCRIPTION

Lamellar tearing is characterized by a steplike cracking, which occurs parallel to the rolling plane in susceptible steels that have experienced large strains in the through-thickness direction. Figure 1 shows a schematic representation¹ of lamellar tearing. The large strains usually result from the restraint of weld thermal contractions and therefore are highly localized. However, the strains could also result from loading a component in the through-thickness direction during service.

Lamellar tearing normally occurs in certain welded structures which are highly restrained. The restraint can be imposed by a massive component or by a smaller one which has been stiffened. Lamellar tearing is commonly reported^{1,3,4} to occur in the following types of structures: nozzle or penetration through a rigid plate, cylindrical stiffeners or closure plates, box structures, and stiffened structural joints such as beam-to-column. Figure 2 shows some examples^{1,4} of these structures. For highly susceptible material, tearing has been reported¹ for low-restraint conditions, such as pullout of lifting lugs and flange-to-web joints in the fabrication of I-beams.

The two basic joint designs that are subject to lamellar tearing are T- (cruciform considered more severe form of T) and corner joints.^{1,3,4} Figure 3 shows examples¹ of these joint designs. These joint types provide high restraint because weld thermal contraction is opposed by compressive forces in the base metal of the components being joined.⁴ Although the butt weld is not considered to be particularly susceptible, some instances of tearing have been reported.^{1,3}

ORNL-DWG 77-19303

Fig. 1. Schematic Representation of Lamellar Tearing Resulting From Weld Thermal Contraction in a Full Penetration T-Joint.

Fig. 2. Structures in Which Lamellar Tearing Commonly Occurs. (a) Penetration through a rigid plate. (b) Cylindrical stiffener and end-closure plate. (c) Box structure. (d) Beam to column.

ORNL-DWG 77-19305

Fig. 3. Typical Joint Designs that Suffer from Lamellar Tearing. (a) Fillet welded T-joint. (b) Full penetration T-joint. (c) Full-penetration cruciform T-joint. (d) Full penetration corner joint.

Lamellar tearing has been found^{1,2,4} from within the lower heat-affected zone (HAZ) (i.e., that region of the HAZ closest to the unaffected base metal) to well into the base metal thickness. The tearing may remain completely subsurface or appear at plate edges or at weld toes.¹

Considerable disagreement among investigators is reported² concerning the time and temperature of the onset of tearing. In fabrication³ and testing² situations, tearing has been reported to occur shortly after passage of the weld pool when previous beads have built up strain. The passing weld pool acts to cause: transient overloading² due to reduction in section support, heating regions into the temperature range where ductility minimums^{3,5} can occur, and additional strain due to thermal contraction. However, others have reported² the tearing to be a room-temperature delayed cracking phenomenon.

The steplike cracking that occurs has several distinct phases. Figure 4 schematically represents these phases based on a description by Farrar et al.⁶ During the initiation phase voids are usually formed by decoherence or fracture of single elongated nonmetallic inclusions or elongated clusters of them lying parallel to the rolling plane. Additional void initiation mechanisms are reported such as splitting along ferrite bands,^{2,7} liquation in reheated HAZ,² intergranular cracking,² hydrogen assisted cracking^{8,9} and strain aging.⁹ However, most investigators^{2,7-9} believe that decoherence or cracking of inclusions is the primary initiation mechanism. The initiated void or tear, which is formed parallel to the rolling plane, is called a "terrace."³ The second phase of lamellar tearing involves the linkage or growth of terraces on common planes. The mechanisms of terrace linkage that have been observed² are necking, microvoid coalescence, "zig-zag" tearing, intergranular cracking, quasi-cleavage, and cleavage. However, the most commonly observed mechanisms are necking and microvoid coalescence.² The third phase of lamellar tearing involves the formation of vertical shear walls³ to connect

Fig. 4. Schematic Representation of the Phases of Lamellar Tearing.

regions of linked terraces on different planes. This third phase produces the steplike appearance of the cracking, and it occurs by ductile shear through regions of microvoids.^{2,5}

Lamellar tearing itself has been reported,⁵ from a fracture mechanics standpoint, as being a subcritical growth phase. Once the crack reaches a critical size through lamellar tearing, brittle fracture becomes the postcritical growth mechanism.

The foregoing description of lamellar tearing indicates that a number of complex interrelated variables control the phenomenon. Disregarding external load application, these variables can be generally grouped into three categories: material, welding, and design.

MATERIAL VARIABLES

The carbon and low-alloy steels that are susceptible to lamellar tearing have low short transverse (ST) ductility. This low ST is related² to three variables: nonmetallic inclusions, matrix properties, and embrittlement. Each of these variables can be associated with the previously described phases of lamellar tearing.

Most investigators agree that nonmetallic inclusions are primarily responsible for the low ST ductility. In conventional steelmaking practice (CON) the maximum sulfur requirement¹⁰ is above 0.025 wt %. Depending upon charge or slagging the attained sulfur level can normally range from 0.010 to 0.030 wt %. The dominant nonmetallic inclusions are sulfides and oxides.^{8,10} The deoxidation practice determines what type of sulfides and oxides are present.^{8,10} For correlation to lamellar tearing, Farrar and Dolby⁶ have classified the deoxidation practices into two categories: non-aluminum-treated and aluminum-treated. Table 2 summarizes the effects of deoxidation practice and inclusion types on lamellar tearing in CON steels.

Semikilled (<0.1 wt % Si) and fully killed (>0.1 wt % Si) are the normal deoxidation practices for the non-aluminum-treated steel grades of interest. In the semikilled and fully killed steels

Table 2. Effects of Deoxidation Practices and Inclusion Types on Lamellar Tearing in CON Steels

Deoxidation Practice	Inclusion Type	Effect on Lamellar Tearing
<u>Non-Aluminum-Treated</u>		
Semi Killed, Fully Killed	Silicates	Become more elongated than the sulfides during hot rolling and are primarily responsible for reduction in ST ductility
	Type I Manganese Sulfides	Dispersed globules are deformed to lozenge-shaped inclusions during hot rolling (aspect ratio 2-20, length 2-200 μm in rolling direction) and generally do not reduce ductility unless there are locally high concentrations
<u>Aluminum-Treated</u>		
Fully Killed	Type II Manganese Sulfides	Rod-shaped inclusions become highly elongated during hot rolling (aspect ratios up to 1000, lengths several mm in rolling direction) and are primarily responsible for the reduction in ST ductility
	Alumina	Although the inclusions are not individually elongated during hot rolling, elongated clusters or galaxies can produce locally poor ST ductility
Fully Killed with Excess Aluminum	Type III Manganese Sulfides	Inclusions become highly elongated during hot rolling and are primarily responsible for the reduction in ST ductility
	Alumina	Same as for fully killed

the oxides are present as silicates and the sulfide is present as type I manganese sulfide.² The type I manganese sulfide normally precipitates in the ingot as dispersed globular inclusions.⁸ During hot working this sulfide is deformed to lozenge-shaped inclusions (aspect ratio 2-20, length 2-200 μm in rolling direction).⁸ It is believed⁸ that oxygen present in these type I MnS inclusions provides solid solution or dispersion strengthening, which prevents them from being readily deformed during hot rolling. Because of the lozenge shape and distribution, the type I manganese sulfide does not generally reduce the ST ductility unless there are locally high concentrations.⁸ Locally high concentrations can be caused by high sulfur levels (≈ 0.5 wt %) or segregation. The silicate inclusions are reported^{2,8} to be principally responsible for reducing the ST ductility because they become more elongated than the sulfide inclusions during hot rolling. The more elongated silicate decoheres in preference to lozenge-shaped sulfide because of greater stress intensification and lower surface energy. Because the silicates are primarily responsible for reducing the ST ductility, the sulfur level can give an incorrect indication of susceptibility to lamellar tearing in non-aluminum-treated steels.

Fully killed (>0.1 wt % Si, usually 0.02-0.08 wt % Al) and fully killed with excess aluminum (>0.1 wt % Si, >0.06 wt % Al) are the deoxidation practices for the aluminum-treated structural steel grades of interest. The oxide is present as alumina clusters or galaxies, and the manganese sulfide is present as type II for the fully killed and type III for the fully killed with excess aluminum.^{2,8,10} Depending upon the specific practice, variations of manganese aluminum silicates and aluminum silicates can also be present.² The type II manganese sulfide inclusions solidify in the ingot with a rod-shaped interdendritic morphology.^{2,8,10} Under certain rolling conditions at low temperatures, the type II sulfide can be deformed to give aspect ratios of up to 1000 and lengths of several millimeters.⁸ The type III sulfide inclusions solidify with an angular morphology.⁸ Because of the high plasticity of the type III sulfide inclusions during

hot rolling, they can become even more elongated than the type II.² The alumina galaxies are trapped by steel dendrites during solidification.¹⁰ Although alumina inclusions are not individually deformed during hot rolling, the groups or galaxies can be deformed into elongated clusters depending upon their original spacing in the ingot. However, it is the sulfides that are reported^{2,8} as primarily responsible for the low ST ductility in the aluminum-treated steels.

An obvious question that can be raised at this point is whether or not non-aluminum-treated and aluminum-treated grades differ in susceptibility. In effect this question asks what is the difference between the silicates, which are dominant in non-aluminum-treated, and the sulfides, which are dominant in aluminum-treated. Oates and Stout¹¹ reported in 1973 that silicates were more detrimental than sulfides. However, Ganesh and Stout² in 1976 and surveys conducted by the Welding Institute¹ reported that the phenomenon of lamellar tearing is too complex to simply relate susceptibility to steel grade or inclusion type. Another study¹² showed that the crack opening displacement to cause tear initiation was independent of inclusion type but depended instead upon projected lengths in the rolling plane. However, this study¹² also showed that lower volume fractions of Type II manganese sulfide were required to achieve high projected lengths.

During sufficient straining in the ST direction, either the interface between the matrix and the elongated inclusions decoheres, or the inclusion fractures to initiate a tear. This tear initiation mechanism can be enhanced by differences in thermal expansion between the inclusions and steel matrix.³ The sulfide inclusions, which contract more than the steel matrix,² can form a void at the interface, thereby providing a site for the tear to initiate. The silicates and alumina,³ which contract less than the matrix, would form residual stresses, which could provide a source of stored energy to aid tear initiation. It is therefore readily apparent that nonmetallic inclusions play a primary role in the void initiation phase of lamellar tearing.

The spacing between the elongated inclusions is an important factor in the linkage of terraces on common planes. This spacing depends upon both the overall inclusion content and any mechanisms that tend to cause segregation. As the inclusion spacing decreases, less energy will be required to tear the intervening matrix. Therefore, the elongated inclusions also play an important role in the terrace linkage phase of lamellar tearing.

Small, finely dispersed inclusions such as alumina are important in both the terrace linkage and shear wall formation phases. These inclusions provide sites for microvoid formation. During tearing, microvoid coalescence is enabled to readily proceed.

The properties of the steel matrix can be important in all phases of tearing. Ferrite-pearlite banding has been reported^{2,8} as causing both initiation and propagation of lamellar tears. This is partially because the ferrite has a lower cleavage fracture stress than the pearlite.⁸ In addition, the lower toughness of the pearlite could provide a crack path. A previously described⁵ model characterizes lamellar tearing as the subcritical crack mode and brittle fracture as the postcritical mode. In terms of this model the fracture toughness of the matrix is very important with respect to tear propagation. The grain size of the matrix is an important factor in determining its fracture toughness. This is because the grain size affects the ductile-brittle transition temperature.

The thermal and strain cycles that result from welding can harden the steel matrix and thereby enhance both crack initiation and propagation capability. Crack initiation by splitting in a coarse-grained HAZ has previously been described.

Strain aging has also been previously described³ as a mechanism that could potentially embrittle the HAZ and reduce ductility. The introduction of hydrogen during welding provides yet another mechanism for assisting crack propagation.

WELDING VARIABLES

The principal effects of welding on lamellar tearing are strain caused by restraint of thermal contraction and a temperature transient caused by heat flow from the passing molten weld puddle. The variables that interact with these effects can be categorized as being related to the welding process or joint design. The joint design variables will be discussed in the next section.

Several welding variables affect lamellar tearing susceptibility. These are reported^{1,3,8,11,13} to be heat input, preheat, filler material, and bead sequence. The effect of increasing heat input or preheat is reported¹³ to improve the postweld ductility. Ganesh and Stout¹³ report four possible factors for the improvement in ductility due to high heat input:

1. increased penetration, which causes interception and blunting of existing tears;
2. increased deposition, which decreases the required number of weld beads and consequent strain cycles;
3. reduction in the cooling rate, which allows stress relaxation;
4. producing a softer and tougher HAZ.

An additional explanation¹ is that higher heat input processes produce lower strength weldments, which will accommodate more of the strain. Although increased heat input has been reported to decrease the susceptibility to failure, it increased¹³ the amount of subcritical tearing. These subcritical tears were located mainly in the coarsened HAZ.¹³ The location and increased amount of subcritical tears might be detrimental during some service loading conditions. In addition, the use of high heat input for highly restrained joints could lead to more overall shrinkage.³ In a survey¹ of fabrication experiences, increasing heat input within a process was reported as ineffective.

The factors cited above for improvement in ductility due to high heat input also apply to preheating. In addition Oates and Stout¹¹ have reported that preheating can raise the temperature of certain materials above their brittle fracture transition, thereby retarding

early propagation of lamellar tearing. For material initially above its transition temperature, they reported a reduced effect from preheat and attributed the small improvement in tearing susceptibility to a reduction in thermal gradients. A survey of fabricators¹ reported no successes with preheat, and one case of increased tearing. In general, when investigators discuss the effects of preheat, they usually^{5,13} add a warning that it may increase contraction strains. If either the recommended material or inspection requirements described in a later section are used, restrictions on the use of preheat are not felt to be necessary.

The proper selection of filler metal is important so that the strength of the base metal is not overmatched. If the weld metal is significantly stronger than the base metal, none of the contraction strain will be accommodated by the weld metal. This results in an increased strain buildup in the base metal with a subsequent increase in tearing susceptibility. Recommendations for limiting the strength of the weld metal are discussed later.

The sequence of weld bead deposition can significantly affect the amount of strain and how localized it is. The use of balanced bead deposition will keep the strain more symmetrical thereby reducing localized buildup. The alternation of welding direction after each pass has also been reported¹³ to reduce initiation of lamellar tearing. The reason for this can be related to the initiation of tearing in multipass welds from a site where straining has been localized during earlier passes. Reversing the welding direction after each pass can reduce the localization of straining.

In addition to the welding variables described above, several techniques have been used to modify the thermo-mechanical effects of welding. These techniques are buttering, peening, and stress-relief heat treatment. In the buttering technique, the weld is made on top of a deposit of filler metal that has been previously applied to the plate and ultrasonically examined. The filler metal deposit consists of one or more layers, which are applied directly to the plate surface or in a gouged out area. Figure 5 (based on ref. .)

ORNL DRG 77-19307

Fig. 5. Welds Made on a Buttered Layer (a) Applied Directly to Plate Surface and (b) Applied in a Gouged-Out Area.

illustrates welds made on a buttered layer. The recommended¹ dimensions for the buttering layer(s) are that it should extend 15 to 25 mm beyond each weld toe and be 5 to 10 mm thick. The purpose of the buttered layer(s) is to accommodate the weld contraction strains and displace the HAZ from the susceptible plate. As a result, the weld metal used for buttering should not overmatch the strength of the plate. Also, it is important to avoid introducing hydrogen and to regulate heat input to produce sound buttering.¹⁴ Although the buttering technique has been reported^{1,14} to be very successful in avoiding lamellar tearing, a few instances of tearing resulting from buttering directly on the plate surface [Fig. 5(a)] have been reported.¹ In addition, one study¹⁵ reported that single buttering layers did not prevent lamellar tearing in a prototypic box section corner joint fabricated from susceptible plate. In general, if the proper controls are placed on the buttering procedure and an adequate size buttered layer is used, this technique should be quite successful in preventing lamellar tearing. However, the cost for using this

technique, the additional time required, and the chance of error introduced by any additional fabrication step must be weighed against buying improved steel.

Peening consists of mechanically working the weld beads by hammer blows or shot impingement to reduce residual stress, and thereby lessen the risk of lamellar tearing. Although peening has been used in the welding industry for a number of years in applications not related to lamellar tearing (prevention of distortion), the technique is not easily controlled and therefore is subject to a wide variation in results. In addition, it is reported¹⁶ to produce adverse effects such as reduction in toughness under certain conditions. A survey¹ of fabricators indicated that peening reduced tearing in only one out of eleven reported cases. Although ASME Code¹⁷ Sect. III Division 1, Subsection NF currently allows the use of peening, it does not appear to be a viable method for reducing lamellar tearing. However, peening of weld metal should not worsen the risk of tearing in susceptible material and therefore need not be prohibited on the basis of lamellar tearing prevention.

Intermediate heat treatment is another technique that has been used to reduce residual stresses. For large components, which would require localized heating, this technique might increase the overall contraction strains. In addition, this heat treatment might cause some decoherence at inclusion-matrix interfaces and thereby increase the amount of indications seen by ultrasonic examination (UT).¹ In general the technique has not been reported¹ to be particularly successful.

DESIGN VARIABLES

The design variables that affect lamellar tearing are related to strain accumulation and concentration in the through-thickness direction. These variables can be divided into two categories: joint design and fabrication sequence. Three major factors in joint design affect the accumulation and concentration of

through-thickness strain. These are weld orientation, balance, and size. The orientation of the weld is obviously an important factor. If a weld is oriented such that it does not cause through-thickness contraction strains, then the likelihood of lamellar tearing should be eliminated. Figure 6, based on refs. 1 and 4, illustrates methods for reorienting the weld to reduce through-thickness contraction. In some T-joints, the weld can be reoriented by using a single electro-slag pass [Fig. 6(a)]. In corner joints the weld can be reoriented by placing the bevel on the plate that would have been through-thickness loaded [Fig. 6(b)]. Redesign of complex structural connections can often reorient the weld to avoid through-thickness strain^b [Fig. 6(c)].

The balance or symmetry of a joint design is an important factor controlling the concentration of strain. Joint designs that deposit the weld from one side cause the strains to concentrate and accumulate on that side. Figure 7 illustrates methods¹ for balancing joint symmetry to reduce the concentration and accumulation of strain.

The size of the weld is an important factor in joint design, which influences the amount of strain accumulation. In multipass welds the size of the weld determines how many passes are required to fill the joint. The number of passes subsequently influences the amount of strain accumulation. Wide groove angles, unnecessary use of full penetration welds instead of simple fillets, and increasing the volume of weld metal to reduce the sectional loading stress are common occurrences that increase the size. Recommendations for requirements to limit the weld size are discussed in a later section.

The fabrication sequence is an important aspect of design, which can have a significant effect on strain concentration in a particular joint. The fabrication sequence determines the amount of restraint that each joint in a multi-joint component will experience. This restraint subsequently influences the amount of strain. If the more susceptible joints in a component can be made initially or as separate subassemblies where restraint levels are lower, weld contraction strains will be allowed to dissipate.

ORNL-DWG 77-19308

Fig. 6. Methods for Reorienting the Weld to Reduce Through-Thickness Contraction Strains. (a) Reorienting the weld in a T-joint by using a single pass electroslog weld. (b) Reorienting the weld in a corner joint by placing a bevel on the susceptible plate. (c) Redesign of a complex structural connection to reorient the weld.

ORNL DWG 77-9309

Fig. 7. Balancing Joint Symmetry to Reduce the Concentration and Accumulation of Strain.

TESTS FOR ASSESSING MATERIAL SUSCEPTIBILITY

The ideal³ test for assessing susceptibility to lamellar tearing must be suitable for production quality control and incorporate the actual joint design, restraint, welding procedure, and material to be welded. However, in practice, while it might be possible to use the actual joint design and welding procedure, and to some degree the restraint, the material sample that is tested may not be representative of the actual area to be welded. This latter situation is due to the heterogeneous nature of ST ductility, which has been reported¹² as varying between ingot yields of the same steel grade, between plates made from different locations within an ingot, and between different locations within the same plate. Unfortunately this situation can manifest itself in steels that have a low overall inclusion content yet have areas of localized segregation. Because of this situation, any destructive test inherently can incorrectly characterize the material whether the characterization be too optimistic or pessimistic. The use of a nondestructive examination (NDE)

technique would then appear to offer the best solution since it would enable surveying an entire plate or just the specific areas to be welded.

Jubb³ has grouped the tests for assessing material susceptibility into the following four categories:

1. tests without simulated or actual welding cycle,
2. tests with simulated temperature and strain cycle,
3. tests with temperature and strain cycles by welding, and
4. tests of a prototypic welded joint.

The dominant variable in these categories is the temperature and strain cycle effects of welding. Although it is desirable to be able to test material without imposing the thermo-mechanical effects of welding, there is considerable controversy concerning the validity if it is not done.

Tests Without Simulated or Actual Welding Cycle

The tests without a simulated or actual welding cycle can be either destructive or nondestructive. Most of the reported work concerning the use of nondestructive tests has been performed at the Welding Institute. Because of the potential benefit of a nondestructive technique, the Welding Institute devoted a considerable amount of their work on lamellar tearing to developing an ultrasonic test. The result¹⁸ of their initial three-year group-sponsored project was the development of a 5-MHz unfocused probe, which used an integrated echo technique to examine discrete levels of thicknesses under both plate surfaces. The integrated echo technique¹⁸ measures the area under the reflections (a function of the size and number of reflections) and uses it to represent the volume fraction of inclusions. A short-pulse-length probe was used to correct for interface echo masking of the layer under the surface being scanned. A normal-pulse-length probe was used for the surface layer opposite the side being scanned, with correction for signal attenuation from intermediate inclusion layers. Corrections were also made for variations in surface finish. Because of the differences

in predominant inclusion types, separate calibration curves were developed to relate integrated echo amplitude to short transverse percentage reduction of area (ST % RA) for aluminum-treated and non-aluminum-treated steels. Wide-scale evaluation¹⁹ of the technique discovered that incorrectly high values of ST % RA were being predicted because of variations in inclusion population and inclusion-steel matrix interface (resulting from different thermal and mechanical treatments) for different grades of steel. From these results it was concluded¹⁹ that the development of a technique applicable to a wide range of steel types was not probable.

Additional work at the Welding Institute¹⁹ on the UT technique has been aimed at simplification of the procedure to eliminate the need for complex calibrations. The need for surface finish corrections was eliminated by using one standard finish. Corrections for attenuation of reflections from the back wall were eliminated by only scanning the surface layer from one side. Instead of attempting to predict ST % RA, direct comparison is made with standards. Although some success has been reported¹⁹ with this simplified technique, it is presently limited to a narrow range of steel types, or to predicting relative variations in a given plate.

However, a fabricator in Italy²⁰ recently correlated ST % RA and ultrasonic test results. In addition, specifications for specific steels to be used in North Sea offshore structures are using both ultrasonic inspection and ST % RA as susceptibility tests.²¹ Even with these reported successes, it still must be realized that the application of ultrasonic examination to the determination of ST % RA in a wide range of materials will be difficult.

Several destructive tests are performed without a simulated or actual welding cycle. While some of these tests require attachment welds for gripping or support, the welds are not meant to provide temperature and strain cycles. The more commonly reported tests are tensile, slice bend, Charpy V-notch (CVN), and analysis of inclusion population.

The ST tensile test is currently the most controversial test for assessing susceptibility. The controversy is because the test offers a standardized method readily applicable to quality control which makes it highly desirable, yet its variability and correlation with lamellar tearing are disputed. The use of the ST tensile test is reported^{12,21} as already being an integral part of steel specifications for critical applications such as offshore structures. In addition, it is reported^{21,22} that this test has been included in recently issued experimental standards in France and Germany. The ST tensile property that is most frequently used is % RA. The % RA is considered²³ to provide a good indication of ST ductility associated with a fracture propagating parallel to the rolling plane. It is also reported¹¹ to be the tensile property that correlates most closely with tearing susceptibility. In addition, it can be more easily standardized than elongation since gage length will vary with plate thickness. The validity of the ST tensile test is usually questioned because of the following:^{3,24}

1. only a small cross-sectional area of material is tested, resulting in a statistically small sampling;
2. the fracture of the test specimen usually occurs near the center of the plate, while the surface region is where lamellar tearing is reported;
3. the results can be greatly influenced by single large inclusions or clusters, while neglecting the steel matrix properties;
4. there are conflicting reports as to the correlation between ST % RA and susceptibility to lamellar tearing.

The concern about the statistically small area sampled is related to the reported¹² heterogeneous nature of ST ductility. Any of the destructive tests that rely on a sampling plan are subject to this error. Although some tests may evaluate a larger area, the total area tested will always be a small fraction of the material it represents. One philosophy that can be used to justify this test is that if a sufficiently high minimum ST ductility acceptance limit

is used, then the poor areas that may escape testing should be small and localized and therefore not create significant tearing. This philosophy is supported by the detailed investigation¹² of ST & RA of the plate yields of two production ingots of fully silicon-killed carbon-manganese steel. Figure 8 shows the location and dimensions of the plates¹² produced from the two production ingots. The testing consisted of 23 sets of tests from ingot A plates and 21 from ingot B plates with six localized specimens per set. Figure 9 shows the reported¹² test locations and the ST & RA values. The ST & RA values of the ingot A plates were higher and more consistent while those for the ingot B plates varied considerably. If the conservative recommended^{2,16} minimum ST & RA acceptance limit of 25% is used, then none of the sets from ingot B would be acceptable, while seven sets from ingot A would have been rejected. This indicates that the use of a conservative minimum acceptance limit can screen out plates with low and widely varying ductilities. It also shows that the limits can be overly conservative.

Fig. 8. Location and Dimensions of the Plates Produced from Two Production Ingots.

Fig. 9. Location of Tensile Tests and ST % RA Values, Mean (Range), for the Plates Produced from the Two Production Ingots.

The location of the ST tensile test has been a concern because it does not test the surface area, where tearing normally occurs. Oates and Stout reported¹¹ significant differences in ST % RA (average of 19.4 vs 2.8%) between specimens with gage lengths centered on plate mid-thicknesses vs 6.4 mm from the surface of 64-mm plate. This could be because surface regions are reduced more during hot rolling and the inclusions located there could be more elongated. However, the restraint of plastic deformation by the hardened HAZ of the weld attaching the testing grips must also be considered. One investigation⁹ has already shown that when the plate thickness is below 30 mm, ST % RA begins to decrease from restraint of plastic deformation by the HAZ of the grip attachment welds. The use of friction welding for grip attachment produces a small HAZ and is

the recommended procedure.⁹ In addition, heat treatment of the attachment welds has been reported as a means of eliminating the restraint from the HAZ.⁹ However, this technique would also heat-treat the base metal and alter its properties. Lamellar tearing occurs near the plate surface because of localized thermo-mechanical effects of the weld cycle. More data need to be developed to indicate whether the surface material is more susceptible.

Large single inclusions or clusters have been reported¹² to reduce the ST % RA. These decreased ST % RA values do not necessarily account for the resistance to further tearing that the steel matrix may have provided. The effect of the large inclusions or clusters can therefore be viewed as making the test more conservative.

Several studies^{5,9,23,25} have shown a correlation between ST % RA and susceptibility to tearing and have made recommendations for acceptance limits. However, another investigation¹¹ has reported an apparent lack of correlation. In one study,²³ 15 steels with known fabrication history of tearing and 20 with known fabrication success were evaluated to determine any correlation between ST % RA, tearing history as a result of fabrication, and type of structure (i.e., degree of restraint). The results of this study were three acceptance limits for ST % RA based upon joint restraint. These minimum ST % RA acceptance limits are 25% for high restraint such as nozzle penetrations, 15% for moderate restraint such as box and cruciform joints, and 10% for light restraint such as fabrication of I-beams. In addition, the following points were made:

1. the acceptance limits are appropriate to yields strengths below 400 MPa (58 ksi);
2. specimen extraction should be from the most critical fabrication region or from a number of locations;
3. at least six specimens should be tested from any area being evaluated;
4. the test is prone to large scatter. Areas having a wide range of ST % RA values indicate low risk of tearing. Only consistently low values, with a low mean and narrow range, indicate a high risk of tearing.

Another study⁹ correlated tearing susceptibility of 40 steels with ST % RA, as ranked by five residual stress levels in the Welding Institute Window Test.²⁶ The study showed a good correlation between susceptibility and ST % RA, with the same scatter trends as previously reported²³ (i.e., scatter increasing as susceptibility decreases). As a result of this study the following minimum ST % RA acceptance limits were recommended: 25% for high restraint, 15% for moderate restraint, and 8% for low restraint. One investigation¹⁵ consisted of correlating tearing in three steels (with varying ST % RA and fabrication histories) during fabrication of five types of test structures with various levels of restraint. The result of this study again was a set of minimum ST % RA acceptance limits, which were: 20% for highly restrained, 15% for moderately restrained, and 10% for lightly restrained. It was also noted that the possible error for measurement for ST % RA was high in the range 0-20%. In a final study,⁵ the incidence of tearing in three large weldment assemblies (representative of pressure vessel fabrications) was compared with the ST % RA of the ASTM A 515 grade 65 steel plates used. The result of the investigation was a guideline of 16% minimum ST % RA for the specific fabrications and material type used. However, in one investigation,¹¹ which compared ST % RA with the critical amount of weld restraint needed to cause tearing during the Lehigh Lamellar Tearing Test, no apparent correlation was found.

The slice bend test^{24,25} is another destructive test that is performed without the thermo-mechanical effects of the weld cycle. The test was developed to provide a means of assessing tearing susceptibility suitable for plant quality control without some of the disadvantages of the ST tensile test. Although the slice bend test offers some improvements in testing technique, it is still susceptible to the sampling problems associated with all destructive tests. The original test procedure²⁵ has been modified. It is currently²⁴ performed by attaching a thin slice of plate to a backing bar and then subjecting the composite to three-point bending such that the through-thickness direction of the slice is in tension. Figure 10 shows the manufacturing and testing sequence²⁴

Fig. 10. Manufacturing and Testing Sequence for the Slice Bend Test. (a) Removal of slice from plate. (b) Attachment of slice to backing bar. (c) Three-point bending of the composite to produce through-thickness strain in the slice.

for the slice bend test. The heavy backing bar enables uniform straining across the thickness, and the amount of strain imposed is controlled by various measuring techniques, which were still being investigated. The criterion for assessing tearing susceptibility is the measurement of total tear length that has progressed through the linkage or shear wall stages for a given testing strain. By relating the testing strain to joint restraint levels, a maximum tear length acceptance limit can be established for various testing strains. Although the slice bend test requires more work on strain measurement technique and establishment of tear length acceptance criteria, the following advantages²⁴ indicate that it should be given further consideration:

1. it is a simple test, which can be readily performed on a plant quality control level;
2. the test evaluates the complete thickness;

3. the test produces realistic lamellar tearing and assesses the important linkage and shear wall stages, thereby enabling it to be more sensitive and possibly reduce the overconservatism of the ST tensile test.

The ST Charpy V-notch (CVN) test is another destructive test that is usually performed without the thermo-mechanical effects of a weld cycle. However, attachments must be welded for testing thin plate or locating the notch near the surface. This test is highly standardized and readily usable for plant quality control. There has been some controversy³ concerning the applicability of the CVN test, since it has a higher strain rate than that associated with lamellar tearing. In addition, because the test only evaluates the plane parallel to the notch, it does not necessarily test the most susceptible region. Two studies report^{5,11} a correlation between tearing susceptibility and CVN tests. One study correlated CVN tests with prototype weldments⁵ while the other utilized the Lehigh Lamellar Tearing Test.¹¹ The result of the prototypic weldment study was the proposal of an acceptance limit for the specific joint types and material that were evaluated. However, another study,⁹ which evaluated susceptibility by the Welding Institute Window Test, concluded that there was no definite correlation. The CVN test appears to be more applicable to characterizing the linkage or shear wall stages of tearing or the brittle fracture mode when the lamellar tear has reached a critical size. Since this test will be sensitive to changes in matrix properties, it would appear to be a good test to run in conjunction with ST tensile tests, as already suggested.⁵ The main problem is that there are no widely applicable acceptance limits available.

The analysis of inclusion population by quantitative metallographic examination is another testing method that is performed without imposing the effects of a welding cycle. The parameters that have been used to characterize the inclusion population are: number, volume fraction, length (parallel to rolling plane), aspect ratio, mean free path, and projected length. Because of the small area scanned per sample, this

method would probably require an extensive sampling plan. The high costs of automatic scanning equipment and large number of tests required do not make this testing method readily applicable as a plant quality control tool. In addition, there is some controversy concerning the correlation between inclusion population analysis and susceptibility to tearing. Generally, the correlation between susceptibility and number or volume fraction of inclusions has been reported^{3,12} to be weak. Correlation is improved by using factors related to inclusion length, as evidenced by the reported¹² correlation between ST % RA and maximum inclusion length. The inclusion projected length, which is the total length of inclusions parallel to the rolling plane per unit area, is reported¹² to relate several inclusion population variables to the direction of fracture propagation. The projected length has shown¹² good correlation with notched bend test maximum crack opening displacement (COD). However, in another investigation,² the inclusion analysis did not provide a good correlation. The possible explanation reported for this poor correlation was that the quantitative analysis did not account for smaller inclusions or matrix properties that affect the propagation of tears.

Tests With Simulated Temperature and Strain Cycles

Simulated weld temperature and strain cycles can be imposed on specimens that have been sectioned from the material to be evaluated. Equipment such as the Gleeble is currently available and capable of providing a simulated HAZ with the proper orientation to the through-thickness direction. However, this type of testing is more suitable for laboratory investigations than for production quality control. One investigation⁹ has reported using this weld cycle simulation technique and then performing tensile tests. The results of this testing showed a decrease in the ratio of ST to longitudinal direction RA.

Tests With Temperature And Strain Cycle By Welding

Two categories of tests within this group use welds. Methods such as the Cranfield Test, Welding Institute Window Test, and Lehigh Lamellar Tear Test use a weld to make a direct assessment of the tearing that results. In contrast, the ST notched bend test utilizes the resultant HAZ from a weld to enable COD testing in the region where tearing normally occurs. These testing methods in this group are still susceptible to the same sampling errors affecting all destructive tests.

Although the ST notched bend test can provide COD measurements of unaffected base metal, the reported studies^{12,27} have examined the HAZ of welds. In these ST notched bend tests^{12,27} full plate thickness specimens are removed and attachments are welded to the two surfaces parallel to the rolling plane. Figure 11, based on ref. 27, shows the manufacturing and testing sequence for the specimens. One weld is a square butt made by electron beam

Fig. 11. Manufacturing and Testing Sequence for ST Notched Bend Specimens. (a) Assembly of components for composite specimen. (b) Welding attachments. (c) Machined specimen. (d) Testing of specimen.

and is meant only to attach an extension block [Fig. 11(b)]. The other weld is a 45° bevel-groove made by the manual shielded metal-arc (SMA) process to attach the stem plate [Fig. 11(b)]. The multipass SMA weld is used to impose through-thickness strains and thermal cycles. After the welds are made, specimens are machined from the composite, and a fatigue cracked or V-shaped notch is oriented parallel to the SMA weld, at various locations in the vicinity of the HAZ [Fig. 11(c)]. During three-point bending, COD measurements are made as crack initiation and propagation occur on a plane parallel to the plate surface [Fig. 11(d)]. The COD to maximum load (δ_{max}) is normally used as the assessment parameter because other values, such as the area under the load vs displacement curve, are too dependent upon test machine stiffness.²⁷ In one investigation,¹² quantitative metallographic analysis of inclusions was performed on samples adjacent to the notch bend test specimens. As previously reported, a correlation was demonstrated between the mean δ_{max} and the inclusion projected length. This correlation was shown to be independent of the type of inclusion. However, attempts²⁷ to correlate notched bend test results with fabrication history or ST % RA have shown discrepancies because the notch location did not coincide with the most susceptible area. The notch bend test has been characterized²⁷ as unsuitable for production quality control because it is a complex and expensive test to run.

The Cranfield Test²⁸ consists of a stem plate and a section of base metal to be tested. Figure 12 shows the details of the Cranfield Test specimen, adapted from ref. 28. The end of the stem plate is beveled such that it forms a 45 or 60° Vee when seated on the surface of the base metal plate. Multipass welding of the VEE, with interpass cooling to allow full thermal contraction, results in a large strain concentration at the root of the Vee. This strain is imposed on the through-thickness direction of the base metal plate and results in lamellar tearing under the root of the Vee when the material is susceptible. The amount of tearing is determined by breaking off the stem plate and measuring the percentage of heat-tinted fracture area. Correlation of test results with fabrication history has been poor.²⁸

Fig. 12. Details of Cranfield Test Specimen.

Because the test conditions are so severe,³ it can only identify highly resistant materials. In addition, variability of testing conditions can make it difficult to apply uniform strain cycles in different tests. One investigation reported⁸ that, because cracking propagated only in the HAZ, poor correlation was obtained when inclusions were outside the HAZ. The use of the Cranfield Test for production quality control would be difficult because of the variability of testing conditions and the severity of the test. No recent investigations have reported success with this test for assessing susceptibility.

In the Welding Institute Window Test,²⁶ a plate of the base material to be tested is inserted through a rectangular hole or window in a restraining plate to form a cruciform joint. Figure 13 shows the details of the test procedure, adapted from ref. 26. The window sides adjacent to the two test plate surfaces parallel to the rolling plane have a Vee bevel. Single-pass, full-penetration fillet welds are initially made in two grooves on one side of the test plate to anchor it. Similar test welds are then made in the two grooves on

Fig. 13. Details of the Welding Institute Window Test.

the opposite side. The restraint provided by the initial anchor welds promotes the occurrence of lamellar tearing in the test plate during the welding of the second side. Visual or metallographic observation of tearing is the criterion for failure. One investigation⁹ has reported the following difficulties with the test:

1. root cracking can induce lamellar tearing and therefore confuse the test results;
2. since the amount of restraint varies as a function of the restraining plate and test plate thicknesses, it is difficult to assess test results quantitatively.

Although this same study⁹ has demonstrated methods to lessen these problems, they are too complex and require carefully reproduced welding procedures. As a result of these problems, the test is not readily applicable to production quality control.

The Lehigh Lamellar Tear Test¹¹ was developed to enable quantitative evaluation of the variables affecting lamellar tearing. The test is

described by its developers as suitable for laboratory use.¹¹ Figure 14 shows the details of the test, adapted from ref. 2. A cantilever beam is welded to the surface of a rigid vertical test plate. Throughout the test, an external load is applied to the cantilever to produce a constant through-thickness restraint on the test plate. Because a multipass weld is used, the load necessary to maintain constant restraint changes after the deposition of each layer. This variable load must be calculated from load lever arm length, width of test plate, thickness of cantilever beam, and the thickness of weld after the deposition of each layer. The criterion for assessing the susceptibility to lamellar tearing is the determination of the critical weld restraint level (CWRL) just necessary to cause tearing. The CWRL is determined by testing at various increasing restraint levels until tearing is detected visually, metallographically, or ultrasonically. The test has been used to examine² a wide range of steel types and the material variables affecting tearing. Modification of the tearing susceptibility assessment criteria was necessary for evaluating welding variables.¹³ The test had to be instrumented to enable recording load vs joint displacement. The modified susceptibility criterion was a

Fig. 14. Details of the Lehigh Lamellar Tear Test.

postweld energy index (E_p), which was calculated from the product of fracture stress and displacement required to cause failure. Although the Lehigh Lamellar Tear Test has demonstrated^{2,11,13} its usefulness as a laboratory tool to study pertinent variables, it does not appear to be readily applicable for production quality control. This is due to both the complexity of the testing procedure and the absence of established acceptance criteria correlated with fabrication history.

Tests of a Prototypic Welded Joint

The results from testing material in a prototypic welded joint are often very difficult to correlate with actual production situations. This is mainly due to the difficulty of duplicating the exact welding conditions and restraint that will be present during production. In addition, as with all destructive tests, the material that is tested may not accurately represent the piece from which it was removed. Because of the potential variability of welding conditions and restraint, the test inherently lacks the ability to quantitatively assess tearing susceptibility. Jubb³ has concluded that although prototypic weldments might be useful for investigating certain parameters, they cannot be recommended for general assessment of tearing susceptibility. This testing method is also undesirable for production quality control because of its complexity and expense. Although several recent investigations^{5,15} have used prototypic weldments to study tearing variables or other test methods, none have proposed its use as a material assessment test.

DETECTION AND REPAIR OF LAMELLAR TEARS AFTER WELDING

Because lamellar tears can remain completely subsurface, such NDE Techniques as visual, dye penetrant, and magnetic particle inspection cannot be used. Radiographic examination cannot be used both because the inclusions can mask defects and because the orientation¹ of the tearing makes detection difficult. Ultrasonic testing is the normal method used to inspect for lamellar tears. However, the

interpretation of UT results can be a problem.^{1,21} Cases of misinterpreted UT indications leading to unnecessary repairs have been reported.¹ Sometimes an angled shear-wave UT examination is needed to detect the presence of the shear walls, which are characteristic of lamellar tearing.²¹ Improper equipment gain settings and acceptance criteria can also cause clusters of inclusions or microstructural bands to be misinterpreted as tears.¹ Unfortunately, the materials that are more susceptible to lamellar tearing contain the type of defects that make UT difficult. For example, thick dirty plates can attenuate ultrasound to the extent that interpretation may be difficult. Recent work at the Welding Institute²² provides an example of this situation. Ultrasonic testing of sections from a box-header that failed during fabrication indicated tearing present in several locations. However, metallographic examination revealed that inclusions had decohered from the matrix, but had not linked to form tears. During tensile testing of these sections, failure occurred on other planes. The above discussion indicates uncertainty in the interpretation of results of UT of production weldments. In addition, reliance on detection by UT to avoid lamellar tearing may be a poor substitute for selection of improved material.

Ultrasonic examination of finished welds or buttered layers does provide a conservative approach. The techniques are sufficiently sensitive such that rejectable tears should not be missed, but instead it is more likely that acceptable indications may be rejected, requiring subsequent repair. When the fabricator decides to use ultrasonic examination instead of selecting material with improved ST ductility, he will be risking repair costs but yet not jeopardizing reliability.

The repair of lamellar tears can be very difficult and costly. One study⁴ indicates that in the repair of highly restrained connections, the repair can be more detrimental than the original weld. This is because at the time of the repair there is usually a larger amount of restraint. The additional mechanical and thermal cycles from repair welding can also simply cause tearing to occur at a greater

depth in the plate thickness. A good example of this situation was provided by metallographic examination²⁹ of a T-butt joint used to attach a circumferential stiffener plate to a cylinder. This joint had experienced extensive tearing during fabrication and was subsequently scrapped. The examination revealed that an attempted repair had caused further tearing below the repair weld.

A successful repair often requires drastic procedures. These procedures might require complete disassembly of the welded joint, grinding or gouging out the joint area and applying buttered layers, and rewelding the joint over the buttering. This type of procedure will of course be very expensive and cause considerable delay. From an economic and schedular viewpoint, it may be more feasible in some situations to scrap a component rather than try to repair it. Because of the potential problems with the repair of lamellar tears, it would appear to be economically justifiable to pay extra for improved material properties rather than risk tearing.

SIGNIFICANCE OF SERVICE LOADING OF MATERIAL SUSCEPTIBLE TO LAMELLAR TEARING

In order to evaluate the significance of lamellar tearing, the effects of service conditions on both existent tears and tear-free material must be considered. Generally, three types of service loadings should be considered: static, dynamic, and fatigue. Although most investigators report only a few known cases of lamellar tearing being initiated or propagated during service loading, critical applications such as nuclear power plants and offshore structures require increased reliability because of stringent service conditions and the consequences of failure.

The effect of static loading on tear-free material, within design limits, must be considered negligible when compared with the highly localized loading produced by the welding cycle. It has been reported³ that the localized strains under a weld can be as high as 2% without even considering stress concentration. Because through-thickness design stresses are limited such that they are significantly below

the yield strength of the material,* strains experienced during service will be significantly less than 0.2% (0.2% offset strain is normally the basis for defining the yield point of most structural materials). Therefore the strain that results from welding can be at least 10 times that caused by service loading. A current group-sponsored project²⁹ at the Welding Institute is investigating the significance of lamellar tearing under static loading. Although this project is still in its early stages with only preliminary results available, a few general trends have been detected. A portion of the work completed involved tensile testing of cruciform test pieces sectioned from a component that had been scrapped because of extensive tearing during fabrication. The amount of lamellar tearing present under the fillet welds of the test pieces varied from none to extensive tearing under both. The results of the tensile testing showed that in most specimens the yield strength of the base material was exceeded before failure despite the presence of extensive tearing. In the test piece with no tearing and in one with tearing under only one weld, failure occurred by necking of the base metal rather than by extension of existing tears, as occurred in the remainder of tests. As would be expected, the failure stress tended to decrease as the amount of existing tearing increased. Although these preliminary results are very limited, they do address the two situations that must be considered: the effects of static loading on existing tears and tear-free material. From these results and the previous discussion of design limits, the welding appears more likely to cause tearing than static service loads. In addition, loads above the yield strength of the base metal are apparently required to propagate tears to failure even though extensive tearing is present initially. However, because the failure stress decreases as the amount of initial tearing increases, failures could occur within design limits if the extent of initial tearing is sufficiently great.

*ASME Code Section III Division 1, Subsection NF limits the design stress intensity (S_m) to a maximum of 1/3 of the yield strength for class 1 components and 5/3 for classes 2 and 3, and for through-thickness loading the design stress is limited to $0.5S_m$.

The significance of fatigue loading with respect to lamellar tearing has received attention recently because of critical applications such as offshore structures. In one study,³⁰ a heat of ABS (American Bureau of Shipping) Grade EH 32 normalized steel with above average static ST properties (ST % RA was greater than 20%) intended for use in an offshore semisubmersible drill rig was tested in fully reversed, axial load-controlled fatigue. Although attachment welds were used to fabricate the ST fatigue test specimens, no lamellar tearing was detected by UT, visual inspection, or metallographic examination of selected specimens. This testing is therefore applicable to the effects of fatigue loading on material that is initially tear-free. The results of the testing showed that the ST direction had several times shorter fatigue life and 20 to 30% lower fatigue strength than the longitudinal direction. These differences were greatest for high-cycle fatigue (greater than 10^5 cycles), where the sensitivity to inclusion content, distribution, size, and shape increases. In the ST direction the fatigue mechanism displayed several rupture modes, consisting of quasi-lamellar tearing (decohesion at inclusion interfaces, tearing, and cleavage) and fatigue striation. However, ductile striation-type rupture dominated the longitudinal direction. Inclusions both initiated and propagated fatigue cracks in the ST direction, while in the longitudinal direction they were insignificant.

The Welding Institute³¹ studied fatigue crack propagation in tear-free material and weldments containing lamellar tears. Four steels with varying susceptibility to lamellar tearing were tested. The tear-free material was investigated with axially loaded, center-notched plate specimens and edge-notched bend specimens, while sections of a cruciform joint were used to study the weldments. In testing of the tear-free material, the steel with the lowest ST % RA had the greatest fatigue crack propagation rate. As previously reported,³⁰ the rupture mode consisted of both fatigue striation and quasi-lamellar tearing. Increases in the amount of quasi-lamellar tearing mode caused the crack propagation rate to increase. However, the results

also indicate that a material must have extremely poor ST properties before the fatigue crack propagation rate is seriously affected. The evaluation of fatigue loading on existing lamellar tears was limited to one steel because tearing did not occur in the cruciform joints of the other three. The amount of tearing present in the joints from the one steel varied from zero to 20% of the load-carrying area. The results of the testing indicated that the fatigue strength did not change as the amount of initial tearing increased. However, this was attributed to the exceptionally low ST properties of the steel. During the testing of the steels that did not contain tears, all the failures initiated at the weld toe. However, on the basis of the initial crack propagation studies, it was predicted that if tears were initially present in these steels they could propagate to failure. For high-cycle fatigue (greater than 10^6 cycles) it was concluded that failure would always occur at the weld toe of the cruciform joint for any of the steels. This is because of the high stress concentration at the weld toe.

Another study³² investigated the effects of three different steelmaking practices on fatigue crack propagation. Heats of ASTM A 533B steel made by conventional steelmaking practice (CON), calcium treatment (CaT), and electroslog remelting (ESR) were tested by use of compact wedge-opening-load fatigue specimens. A ST % RA of 20% for the CON material indicated that its ST ductility was not low. The results showed that the fatigue crack growth rate in the ST direction of the CON material was considerably higher, while the CaT and ESR materials had significantly improved isotropy with overall improvement and reduction in scatter. The improvement in fatigue crack growth rate was attributed to alteration of inclusion morphology and distribution. Observations of the fracture surfaces of the CON material agreed with the previously reported studies,^{30,31} which showed inclusions affecting the ST direction but not the longitudinal direction. In addition, the same quasi-lamellar tearing decohesion of inclusions was shown to be responsible for the increased growth rates in the ST direction.

The following conclusions can be drawn from the results of the three previously described studies. The fatigue properties of tear-free steels made by CON can show anisotropy in the ST direction even though the ST ductility is above levels where lamellar tearing occurs. However, stress concentrations at the root or toe of welds would likely be more detrimental in tear-free material unless the ST ductility is very low. In steels with initially existing lamellar tearing, the tears appear to be most detrimental to fatigue loading. For high-cycle fatigue (greater than 10^6 cycles), stress concentrations at the root or toe of the weld may be more detrimental than existing tears or poor ST ductility.

In ASME Code¹⁷ Subsection III-NF, linear supports of classes 1, 2, 3, and MC have fatigue stress range limits (as specified in Section III Appendices Article XVII-3000) for loading cycles greater than 20×10^3 cycles. The limits are based on the stress category (type of member and loading) and the number of cycles. The allowable stress ranges for full and partial penetration T-joints transmitting a load in the through-thickness direction are penalized by approximately 40 and 60%, respectively. Since these limits account for weld stress concentrations that can be potentially more detrimental, the design margin against lamellar tearing during fatigue loading appears adequate. However, there are no fatigue design limits for plate-and-shell type supports or for loading cycles less than 20×10^3 . In discussions with members of the ASME Code Working Group on Component Supports (SG-D) (SC III), we were not able to ascertain whether fatigue limits were omitted in these situations because of their insignificance.

Recent investigation of the effects of dynamic loading with respect to lamellar tearing has mainly been limited to CVN testing of steels to assess tearing susceptibility. However, some investigations³ of the effects of shock loading welded structures have been performed. In a study³³ at the Naval Construction Research Establishment in Scotland, explosion tests of full-penetration T-joints were performed on three steels: H.Y. 80, O.T. 35 (a U.K. grade of quenched-and-tempered C-Mn-Ni-Cr Steel), and B quality (a U.K. grade of fully

killed and normalized C-Mn steel). Both the Q.T. 35 and B quality steels had histories of lamellar tearing during fabrication, while the H.Y. 80 is not normally considered susceptible. The results of the explosion tests showed that the Q.T. 35 and B quality steel T-joints failed completely by lamellar tearing, while the H.Y. 80 T-joints suffered only limited ductile tearing at the weld toe. These results demonstrate that dynamic loading can cause the formation and propagation to failure of lamellar tears. These tests again show that if the steel has sufficient ST ductility, the stress concentration at the weld toe can be the limiting factor in dynamic loading, as was the situation for fatigue.

Reduced ST CVN properties have been reported^{5,10,11} for tear-free A 515, A 516, and A 533B steels made by CON. In addition, reduced ST dynamic tear (DT) properties have been reported¹⁰ for tear-free A 533B steel made by CON. These results along with the limited explosion testing of weldments indicate that the ST directions of these steels are more susceptible to failure by lamellar tearing and brittle fracture mechanisms during dynamic loading. Although no specific investigations of steels with existing tears are known to this author, the presence of existing cracks can only decrease the resistance of the material to failure during dynamic loading. Since selection of material with improved properties is the only design procedure for ensuring resistance to failure during dynamic loading, mandatory ST ductility requirements should be specified for Subsection III-NF components that may be dynamically loaded.

RECOMMENDATIONS FOR AVOIDING LAMELLAR TEARING DURING FABRICATION OR SERVICE LOADING

The most effective means for avoiding lamellar tearing is through the use of material with improved ST ductility. However, selecting better material increases costs. With the advent of inspection requirements and more sensitive UT techniques, the detection of lamellar tears that result from fabrication has increased. Because these tears must be eliminated by costly and sometimes ineffective repairs or by

disassembly and replacement of the defective material, the increased costs for improved material are now more justifiable. Improved materials are already being used in critical service applications. Requirements for steels to be used in critical components of offshore structures have already specified lower sulfur contents, minimum ST tensile strength, minimum ST % RA, and maximum allowable inclusion content.^{21,30} Table 3 shows some selected material requirements³⁴ for critical components in North Sea offshore structures.

Table 3. Selected Material Requirements for Critical Components in North Sea Offshore Structures

Offshore Platform	Application	Maximum Sulfur (%)	ST % RA
B.P. Forties	Node tubes	0.010	20 (mean of 6)
			15 (min individual)
Shell Brent	Nodes	0.015	>35 (mean of 6)
	Node type bracing	0.015	>35 (mean of 6)

Figure 15 shows two design paths for avoiding lamellar tearing during fabrication or service loading. One path is required for class 1 and the other may be followed for classes 2, 3, and MC component supports. The information contained in this figure provides a synopsis of the conclusions from the foregoing assessment of lamellar tearing. The difference between the two paths is that the one for class 1 component supports requires the use of material with improved ST ductility, while the path for the other classes does not. Although material improvement is preferable, less critical applications, cost, and availability of material may make the alternate path more desirable and therefore justify it being an option. However, the reliability of the path for classes 2, 3, and MC component supports is assured by two mechanisms. First, the service loading must always be considered. For dynamic loading, improvement of the material's ST properties is mandatory. Second, ultrasonic examination of the finished weld or buttered layer is required.

ORNL-DWG 77-19302

Fig. 15. Design Paths for Avoiding Lamellar Tearing During Fabrication of Service Loading of Section III Division 1, Subsection NF Component Supports.

The following summary highlights the conclusions presented in Fig. 15. The avoidance of lamellar tearing must begin at the design stage. The service loading should be considered, and mandatory ST material requirements specified for dynamic loading. The joint design should be optimized by balancing the joint, reorienting the weld if possible, and minimizing the size of the weld. The fabrication sequence should be optimized by welding susceptible joints first or by using subassemblies to minimize the restraint. Material susceptibility to tearing can be avoided by either replacing the hot-rolled steel with another product form or selecting material with improved ST properties. A decision to replace hot-rolled steel with a casting or forging must weigh the economic consequences. The improvement of the hot-rolled steel should be aimed at both the inclusions and the matrix. The addition of rare earth metals or the use of advanced steelmaking techniques such as calcium treatment or electroslag remelting can be used to reduce sulphur and oxygen levels and alter the shape, size, type, and distribution of inclusions. The matrix properties should be upgraded by reducing the banding and improving the toughness. The test that is currently most applicable to material assessment in a production environment is ST Z RA. When this test employs a sufficient sampling plan with conservative acceptance limits, it should provide an adequate means of assuring freedom from tearing. The use of the ST CVN Test provides a method to evaluate the toughness of the matrix. However, additional work is required to establish acceptance criteria for this test.

Several considerations are important in reducing the risk of tearing during fabrication. The filler metal should be controlled so that it does not overmatch the strength of the base metal. The localization of contraction strains should be reduced by using a balanced bead deposition sequence. Embrittlement of the HAZ should be avoided by using techniques to eliminate the introduction of hydrogen. The buttering technique can be used to lessen the risk of tearing in materials without improved ST properties or for repair. Ultrasonic inspection should be required when material with unimproved ST properties is used or when the buttering technique is employed.

ASSESSMENT OF ASME CODE REQUIREMENTS

Currently ASME Code Section III Division 1, Subsection NF has only one requirement to deal with lamellar tearing or poor ST ductility. This requirement limits the stress at the contact surface of a weld transmitting a through-thickness load to 50% of the design stress intensity (S_m). However, the effect of this requirement has been to cause designers to increase the size of welds to reduce the stress. Since increased weld size worsens the risk of lamellar tearing as previously described, the Code committee is currently planning to eliminate this stress limitation from Section III Division 1, Subsection NF. Since the design stress intensity (S_m) would still be considerably below the yield strength, as previously discussed, this should not increase the risk of tearing. As a replacement for this limitation on stress, a limitation should be placed on the size of the weld. One possible method would be to limit the cross-sectional area of a weld at the contact surface where it produces a tensile load in the through-thickness direction. The limitation on the weld cross-sectional area should be based upon the load-carrying area of the smaller of the two members being joined. An allowance must be made for additional reinforcement that the welder may add. Typically, this additional reinforcement could be 10% on either side of the weld. Therefore, a possible requirement might be that the cross-sectional area of a weld at the contact surface where it produces a tensile load in the through-thickness be less than 120% of the load-carrying area of the smaller of the two members being joined.

The specifications permitted by ASME Code¹⁷ Section III and Code Case N-71 (formerly 1644-6) for materials that are potentially susceptible to lamellar tearing are shown in Table 4. It should be remembered that susceptibility to lamellar tearing depends largely upon the steelmaking practice used to manufacture hot-rolled plates and shapes of carbon and low-alloy steel. Materials produced to some of the specifications listed in Table 4 will be more susceptible than others. However, this difference in susceptibility is not necessarily due to different requirements in the specifications.

Table 4. Material Specifications Permitted by ASME Code Section III-NF
But Potentially Susceptible to Lamellar Tearing

Specification	Description	Applicable Component Support Classes			
		1 ^a	2 ^b	3 ^c	MC ^d
SA-285 ^e	Carbon steel plate for pressure vessels	/	/	/	/
SA-442	Carbon steel plate for pressure vessels	/	/	/	/
SA-515 ^e	Carbon steel plate for pressure vessels	/	/	/	/
SA-516 ^e	Carbon steel plate for pressure vessels	/	/	/	/
SA-537	Carbon steel plate for pressure vessels	/	/	/	/
SA-299	Carbon steel plate for pressure vessels	/	/	/	/
SA-204	Low-alloy steel plate for pressure vessels	/	/	/	/
SA-302	Low-alloy steel plate for pressure vessels	/	/	/	/
SA-533	Low-alloy steel plate for pressure vessels	/	/	/	/
SA-36 ^e	Structural carbon steel plate and shapes	/	/	/	/
A 572 ^e	High-strength low-alloy steel plate and shapes	/	/	/	/
A 588	High-strength low-alloy steel plate and shapes	/	/	/	/
SA-612	Carbon steel plate for pressure vessels		/	/	/
SA-283 ^e	Structural carbon steel plates			/	/

^aFrom ASME Boiler and Pressure Vessel Code Sect. III, Div. I Appendices, Tables I-1.1 and I-11.1; ASME Code Case N-71, Table 1.

^bFrom ASME Boiler and Pressure Vessel Code Sect. III, Div. I Appendices, Tables I-7.1 and I-12.1; ASME Code Case N-71, Table 2.

^cFrom ASME Boiler and Pressure Vessel Code Sect. III, Div. I Appendices, Table I-8.1.

^dFrom ASME Boiler and Pressure Vessel Code Sect. III, Div. I Appendices, Table I-10.0.

^eHistory of lamellar tearing, reported by S. Ganesh and R. D. Stout, *Weld. J. (Miami)* 55(11): 341-s-354-s (November 1976), or D. A. Canonico, ORNL, private communication.

These specifications generally allow a wide range of steelmaking processes (open-hearth, basic-oxygen, electric-furnace, vacuum-arc remelt, or electroslag remelt), deoxidation practices (rimmed, capped, semikilled, killed, killed plus aluminum for fine grain practice), sulfur content (0.04-0.05% maximum), and silicon content (0.15-0.30%). Therefore disallowing the use of certain specifications will not be an adequate solution to the lamellar tearing problem. However, the use of an ST % RA requirement will force the designer and the steel producer to select the steelmaking practices necessary to improve ST ductility. Table 4 shows that five of the material specifications allowed for class 1 component supports have a reported history of lamellar tearing. Because of the critical nature of class 1 components, this situation highlights the need for mandatory ST ductility requirements in class 1 component support materials that will contain a weld transmitting a load in the through-thickness direction.

Since the redesign of weld joints, other than completely eliminating through-thickness strain in rolled plates or shapes, cannot always eliminate tearing in susceptible material, mandatory joint designs do not seem appropriate. However, the addition of preferred joint designs to Code¹⁷ Subsection III-NF Fig. NF-3291(a)-1 requirements for plate and shell supports and the CODE¹⁷ Section III Appendix XVII-2450 requirements for linear supports would be appropriate. Examples of some preferred joint designs are discussed in a previous section.

The ASME Code Subgroup on Fabrication and Examination (SC III) is currently formulating requirements for welds that transmit a through-thickness load in rolled plates and shapes of Subsection III-NF component support primary members greater than 16 mm (5/8 in.) in thickness. The currently³⁵ proposed requirements provide options to either ultrasonically examine finished welds, weld on an ultrasonically examined inlay or overlay, or test the base metal to meet an ST % RA of 20% for a single test. In addition, the minimum specified tensile strength of the filler metal is not allowed to exceed that of the base metal by more than 83 MPa (12 ksi). These requirements are aimed at the Subsection III-NF fabrication and installation article

and do not interface with the materials and design articles as recommended in Fig. 15. The proposed requirements should incorporate design considerations of component support class and service loading. Mandatory materials requirements should be included for class 1 component supports or service conditions that may experience dynamic loading.

The decision to limit requirements to material greater than 16 mm (5/8 in.) in thickness is not totally supported by a reported¹ survey of fabricators. In this survey lamellar tearing was reported by 20% of the fabricators in situations in which the plate thickness did not exceed 13 mm (1/2 in.). Although 95% of the fabricators reported tearing to occur in thicknesses between 13 and 64 mm (1/2 and 2 1/2 in.), the potential for tearing in highly restrained thin plates cannot be overlooked. In addition, a recent study³⁶ has shown that the inclusions in thin plate can be more elongated than those in heavy plate if the rolling ratio (ratio of primary rolling to cross rolling) is not kept low. As a result of the above considerations, it may be prudent to require improved ST ductility in all thicknesses of class 1 component supports, and require the use of one of the three options in thicknesses above 16 mm (5/8 in.) for all other classes.

As previously discussed, the optional use of ultrasonic examination of finished welds or welding on an ultrasonically examined buttered layer for materials that do not have improved ST ductility is an acceptable procedure if component support class and service loading are considered. The methods described for ultrasonic examination and buttering in the proposed requirements appear to follow the procedures recommended in the literature. In addition, the limitation on filler metal strength is a good requirement.

The proposed requirements for specifying a minimum ST % RA need to be revised. As previously recommended, the ST % RA requirements should be limited to steels with yield strengths less than 400 MPa (58 ksi). The requirement for a single tensile test with a minimum ST % RA of 20% needs to be modified to provide a more conservative acceptance limit. The need for a higher ST % RA can be justified

because of the large variations that commonly occur between 0 and 20%. Dolby has recently reported³⁷ that although Welding Institute experience has shown that an ST % RA of 20% (for a set of six specimens) is adequate to avoid tearing in highly restrained joints, a more conservative minimum ST % RA such as 25% is necessary to make allowance for such factors as inclusion segregation. In addition, a recent Welding Research Council Bulletin,³⁸ which presents an international bibliography on through-thickness properties and lamellar tearing, points out the need for statistical control over ST % RA requirements because of their variability. As an example, recent changes in specifications for materials for offshore construction are cited. Whereas two to three years ago an ST % RA of 20% was used, recent specifications require a minimum individual value of 10% with a 35% minimum average for a set of six specimens.³⁸ A minimum ST % RA of 25% is the acceptance limit used for the most reliable steel grades in French and German standards.²¹ The testing of a set of six specimens should also be required to improve the statistical representativeness of the test. Existing specifications are currently requiring sets of 3 to 6 specimens. The size of specimens and the extraction procedure should be standardized. Since it is advantageous to use a large specimen diameter and possibly include the plate surface regions in the specimen gage length, these factors should be considered when establishing standard specimen size and extraction procedures. In addition, requirements should be established for the welding of grip attachments to plate surfaces. The range of product thicknesses from a given heat that a set of tests can represent must also be specified. As previously reported,³⁶ the amount of reduction can affect the degree of inclusion elongation and thereby influence ST ductility.

CONCLUSIONS

A need is evident to establish requirements to reduce the risk of lamellar tearing in critical applications such as Nuclear Power

Plants. However, because of the controversy surrounding the various aspects of lamellar tearing, it has been difficult to establish universally accepted requirements. The design paths shown in Fig. 15 along with the specific recommended acceptance limits and testing conditions provide usable requirements that are based upon both fabrication experience and research programs. While it may appear to some that these requirements are too conservative, this apparent conservatism is needed to bridge the gaps in the controversial aspects of lamellar tearing.

The results of this assessment indicate that the improvement of material properties is undoubtedly the best approach for reducing the risk of lamellar tearing. However, it was also recognized that under certain service loading conditions in noncritical applications, the use of ultrasonic examination or buttering can provide acceptable methods for reducing the risk of tearing. This situation highlights the fact that the requirements that are recommended as a result of this assessment were aimed at both reducing the risk of lamellar tearing and providing flexibility to fabricators when possible.

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