

Lamellar tearing in welded steel fabrication

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Please note

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You will see that many of the photographs are, regretfully, insufficiently
clear to show some of the details described in the text.
Please accept our apologies for this.*

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CONTENTS

3 FOREWORD

3 INTRODUCTION

4 DESCRIPTION OF LAMELLAR TEARING

4 What is lamellar tearing ?

4 For tearing to occur, three conditions must be satisfied

4 What points characterise tearing and enable it to be distinguished from other forms of cracking ?

5 What causes lamellar tearing ?

6 OCCURRENCE AND AVOIDANCE OF THE PROBLEM

6 Type of structure: Nozzle or penetrator set through a rigid plate. Stiffeners or end closure plates in cylindrical structures. Stiffened joints and box structures. Other types of structure

8 Joint design: T joints. Corner joints. Butt joints

10 Weld sizes

10 Materials: Steel type. Steel strength level. Steel thickness. Steel cleanness (inclusion content). Product type. Negotiation with steel suppliers. Ultrasonic testing of plate. Destructive testing

14 Welding factors: Welding process. Choice of consumable. Welding conditions. Welding techniques

16 DETECTION OF LAMELLAR TEARING AFTER WELDING

FOREWORD

The C298 Sponsor Group was formed in 1969 to investigate specific aspects of lamellar tearing following background work in The Welding Institute's general research programme.

One of the immediate tasks of the Group Sponsored project was to bring together unpublished information on lamellar tearing and to present this in a small booklet which would give advice to the welding engineer or designer on the problem and methods for its avoidance.

The present booklet includes this essential information although the work of the Sponsor Group is continuing and as more knowledge is obtained — for example on material selection — it is hoped to incorporate this in revised editions of the booklet.

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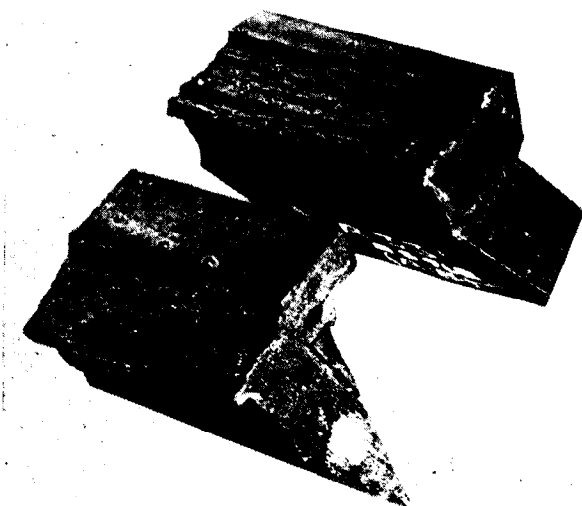
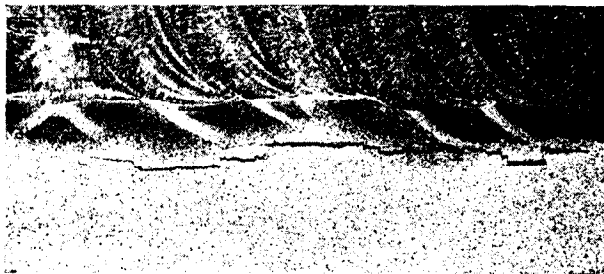
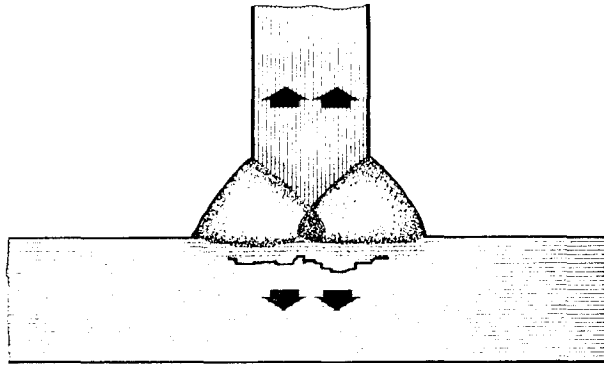
INTRODUCTION

The aim of this booklet is to provide, in an easily assimilated manner, information for the designer and welding engineer which will help him to reduce the incidence of lamellar tearing in welded structures and to overcome the problem should it occur. In addition, the booklet provides general information about lamellar tearing for anyone concerned with welded steel fabrications. A description of lamellar tearing is given and the causes of the cracking briefly discussed in metallurgical terms. The practical occurrence of the problem with respect to both joint design and structure types is discussed in some detail, because it is at the design stage that many precautions can be taken to avoid lamellar tearing. Much work needs to be carried out particularly in connection with aspects of material selection, but information which is currently available is presented. Problems can be encountered in both the detection and subsequent repair of lamellar tearing and both of these topics are discussed.

The information presented has been collected from three major sources:

- 1 The results of a questionnaire distributed to members of The Welding Institute lamellar tearing contract sponsor group and representing both fabrication and user industries. Thirty-five replies were received.
 - 2 A review of the literature, particularly those parts of it which deal with the practical occurrence of the problem. Lamellar tearing is not restricted to the UK and has been extensively reported in Europe, the USA, and Japan. Some of the data from these sources has been incorporated.
 - 3 Visits to UK fabricators and users made over the past few years have led to the retrieval of much first-hand information about instances of lamellar tearing and the methods of overcoming the problem. This data has been incorporated anonymously.
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DESCRIPTION OF LAMELLAR TEARING



What is lamellar tearing ?

Lamellar tearing is a cracking phenomenon which occurs beneath welds, and is principally found in rolled steel plate fabrications. The tearing always lies within the parent plate, often outside the transformed (visible) heat-affected zone (HAZ), and is generally parallel to the weld fusion boundary.

For tearing to occur, three conditions must be satisfied

- 1 *Strains* must develop in the short transverse direction of the plate. These strains arise from weld metal shrinkage in the joint but can be greatly increased by strains developed from reaction with other joints in restrained structures.
- 2 *The weld orientation* must be such that the strains act through the joint across the plate thickness, i.e. the fusion boundary is roughly parallel to the plate surface.
- 3 *The material* must be susceptible to tearing, e.g. in the joint shown the horizontal plate must have poor ductility in the short transverse (through-thickness) direction.

What points characterise tearing and enable it to be distinguished from other forms of cracking ?

- 1 In section it has a stepped appearance with long horizontal portions and short vertical steps.
- 2 It often lies just outside the visible HAZ, parallel to the weld fusion boundary and the plate surface.
- 3 It can be completely subsurface and difficult to detect even using non-destructive methods.
- 4 The surfaces of the cracks are fibrous, woody, and characteristic of low ductility fractures.
- 5 It is not often associated with hydrogen-induced HAZ cracking and may well occur even when adequate precautions against hydrogen-induced cracking have been taken.

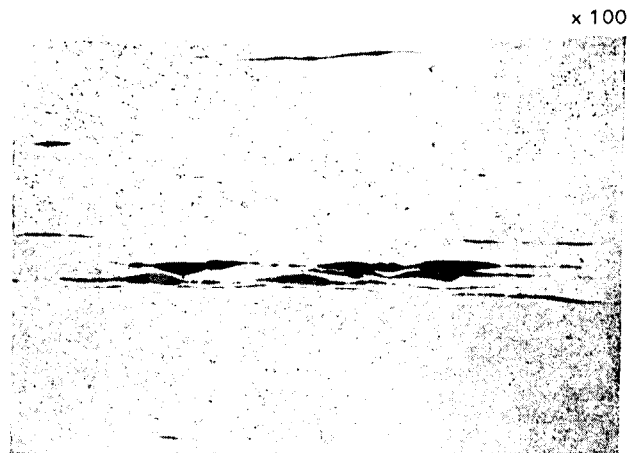
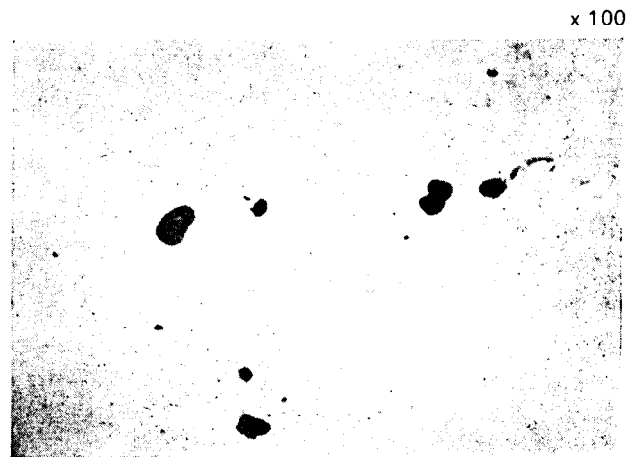
- 6 In some cases cracking may be very extensive, extending for several feet and being readily visible on plate edges or at weld toes. In some instances complete detachment may take place causing the 'pull out' type of fracture which has been reported in the literature.

What causes lamellar tearing ?

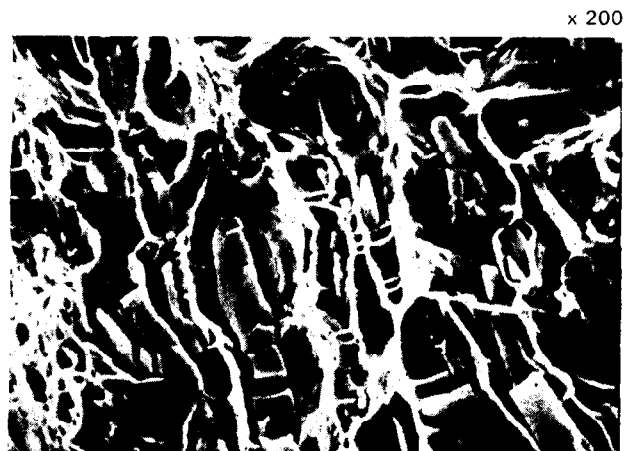
Three factors have been outlined as being contributory to the occurrence of lamellar tearing. Two of these — structural restraint and joint design — will be covered more fully in later sections. The third is the occurrence of poor short transverse (ST) ductility in rolled plate. It is not the intention here to discuss the detailed metallurgical factors responsible for the reduced ductility, but it is necessary to have some understanding of the problem so that the reasons for applying some of the remedial and precautionary measures can be fully appreciated.

It is now generally accepted that the main reason for low ST ductility lies in the inclusion content of the plate. All the steels in common use in structural and pressure vessel applications contain considerable numbers of inclusions, mainly of the manganese sulphide, manganese silicate, and oxide types.

The inclusion content of an as-cast steel depends on numerous factors such as the type of steel, deoxidation practice, composition, position in the ingot, etc. The inclusions are usually formed as spheres, eutectic films, or small angular particles in the solidifying ingot.

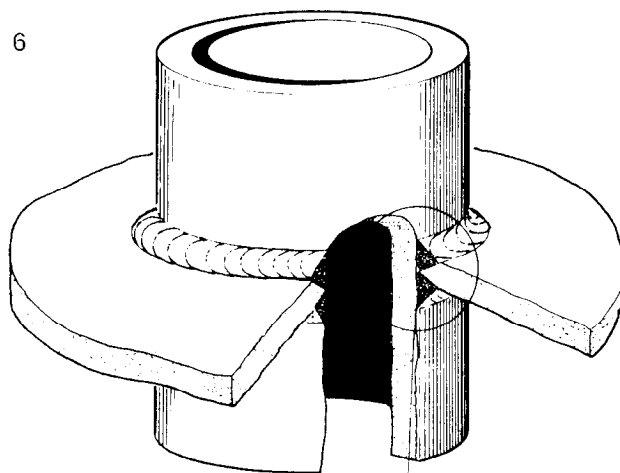


When the ingot is rolled to form steel plate the inclusions deform into plates or discs parallel to the plate surface. Different types of inclusions deform to different degrees relative to the steel matrix and some may fragment during rolling.

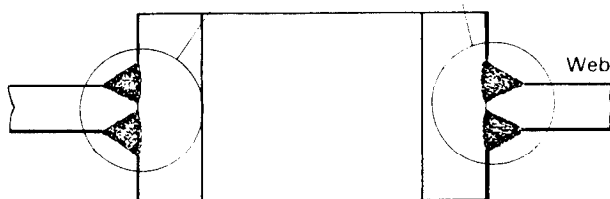
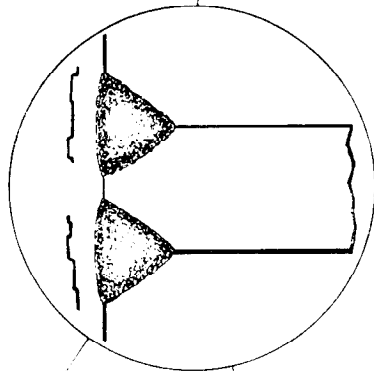


High concentrations of elongated and/or fragmented inclusions seen here on a fracture surface, are responsible for poor ST ductility and the incidence of lamellar tearing in steels.

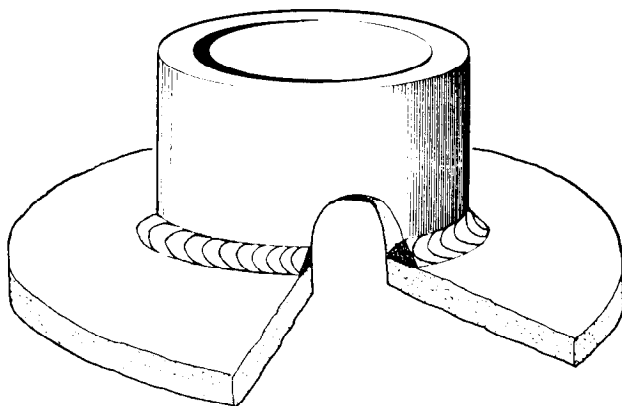
It is important to note that only a small percentage of steel plates are susceptible to tearing, even though all steels contain deformed inclusions. Only in certain plates are the concentrations of inclusions, coupled with unfavourable shape and type, sufficient to give a risk of tearing. Also, of the potentially susceptible steel plates, only a further small percentage is incorporated into the critical joints and structures which satisfy the other two conditions necessary for lamellar tearing to occur.



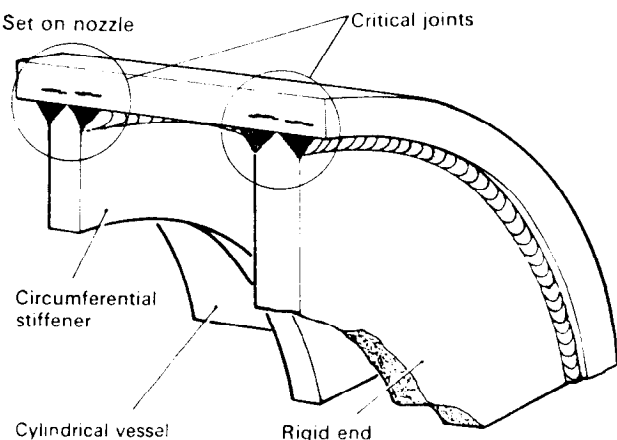
Set through nozzle



Insert through Veerendel type girder



Set on nozzle



Critical joints

Circumferential stiffener

Cylindrical vessel

Rigid end

OCCURRENCE AND AVOIDANCE OF THE PROBLEM

Type of structure

Lamellar tearing occurs at certain critical joints usually within large welded structures involving a high degree of stiffness and restraint. Restraint may be defined as a restriction of the movement of the various joint components that would normally occur as a result of expansion and contraction of weld metal and adjacent regions during welding. From an analysis of fabrication failures and the results of the questionnaires it appears that three major categories of structure type are commonly associated with the problem.

Nozzle or penetrator set through a rigid plate. Cracking is liable to occur in a rolled plate penetrator set through a vessel wall or end, or in a fabricated insert in the web of a large girder. In both cases any tearing will occur in the penetrator or insert. About half the fabricators who suffered tearing reported it in this type of structure.

The risk can be reduced by the use of set-on rather than set-through nozzles. This usually involves the use of a compensating plate and a slight risk of tearing. The incidence of tearing in the shell plate is much less than in the penetrator plate.

Stiffeners or end closure plates in cylindrical structures. Lamellar tearing is a risk in shell plates adjacent to end closures or tube plates, or in cylindrical wrapper plates when these are stiffened by internal ribs. Reports of cracking in this type of situation are numerous and more than half the fabricators answering the questionnaire had encountered tearing in this type of structure.

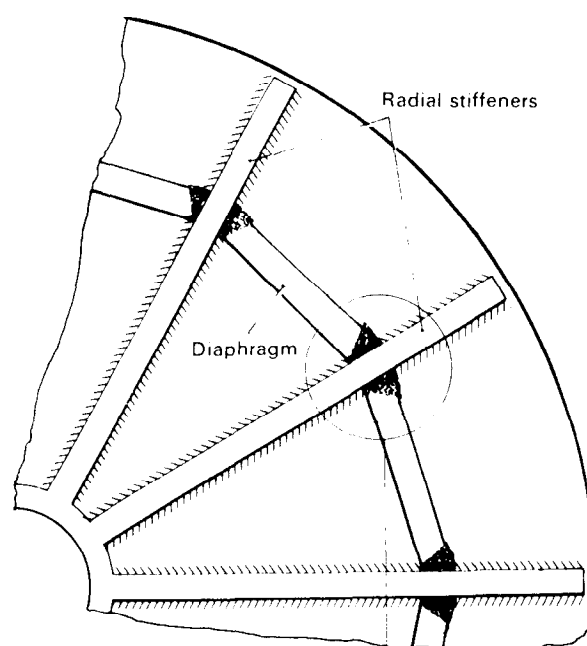
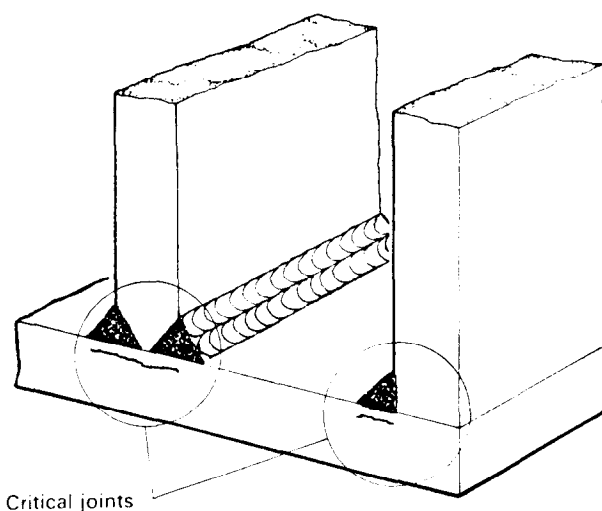
In a number of cases tearing was completely subsurface and difficult to detect.

To reduce the risk of tearing, modifications to joint details, materials, or procedures are usually required; these are considered in detail in a later section.

Stiffened joints and box structures. This category is diverse and covers a range of structures from simple box columns to complicated structural frameworks incorporating intersections of large girders.

Most fabricators with experience of lamellar tearing have encountered it in this type of structure (> 70% from the questionnaire). A number of typical situations which have been reported in the literature are shown.

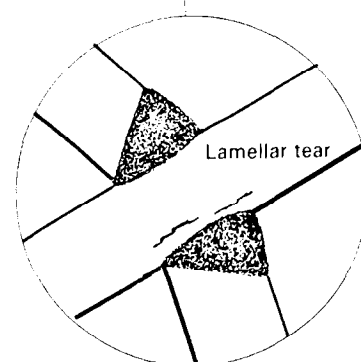
Again to reduce the risk of tearing, modifications must be made to joint details, materials, and procedures.



Other types of structure. In extreme cases tearing can occur in situations of apparently low restraint. It would appear that the materials in these cases are highly susceptible. Two cases which have been reported are:

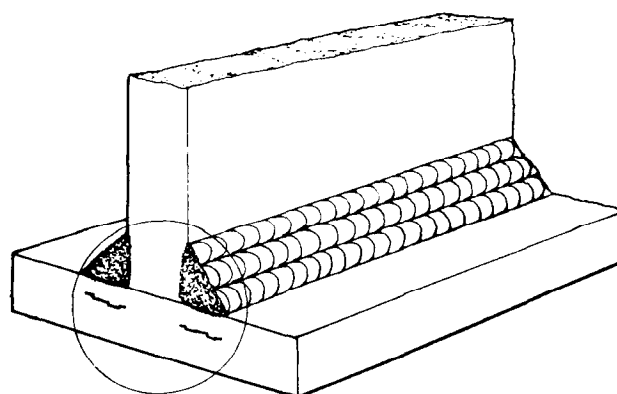
- 1 Pull out of lifting lugs from the parent plate.
- 2 Lamellar tearing in flange-to-web joints in fabricated I beams.

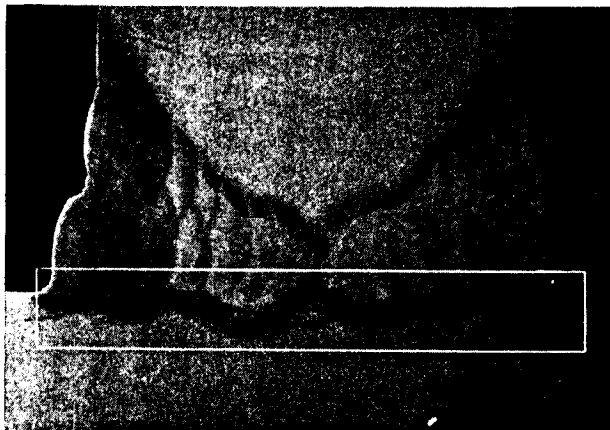
It is important to be aware that lamellar tearing can be a problem in apparently simple unrestrained joints if the material is sufficiently susceptible. If the service application is a critical one, e.g. lifting lugs, it is essential that inspection for lamellar tearing should be carried out even if the risk of occurrence is considered small. Care should be taken to reduce the stress through the thickness of critical joints, loaded in service, to a minimum.



Points to note

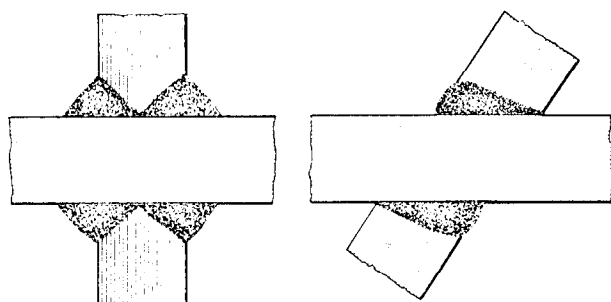
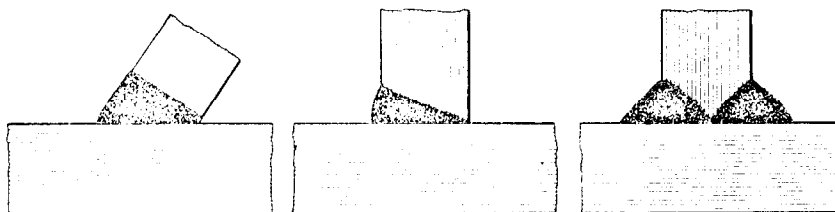
- 1 Be aware of the risk of tearing in the types of structure described above and be prepared to pay particular attention to joint details to minimise the risk, as discussed in the next section.
- 2 Do not ignore the risk of tearing in apparently simple structures if the applications are highly critical.



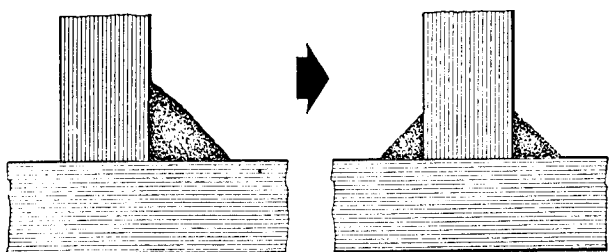
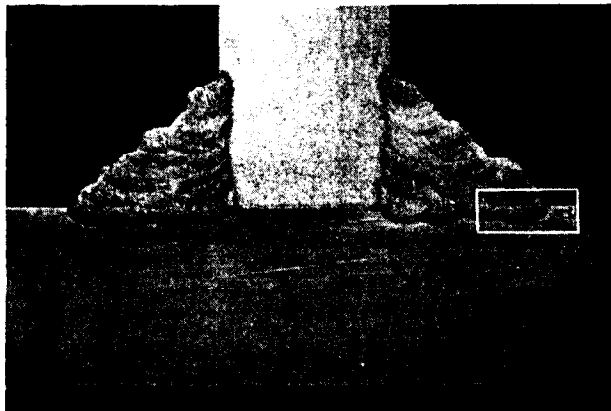


Joint design

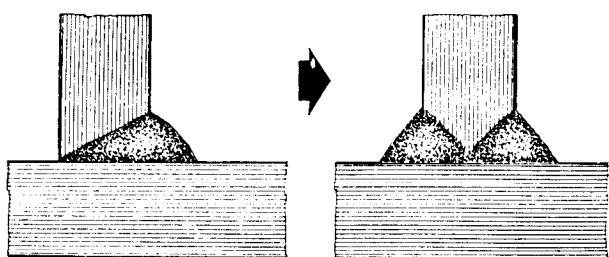
T joints. Full penetration T joints with single- or double-sided full penetration butt welds are common sites for lamellar tearing and were reported in almost all replies to the questionnaire. The cruciform joint can be considered to be a more severe form of the T joint since bending of the susceptible plate in the region of the weld is not possible.



T joints with simple fillets rather than full penetration welds do not give such severe problems and less replies reported tearing with this type of joint than with the full penetration T joint. An example of cracking with simple fillets is shown in the photomicrograph.



In addition balanced double-sided welds appear to present less risk than large single-sided welds.

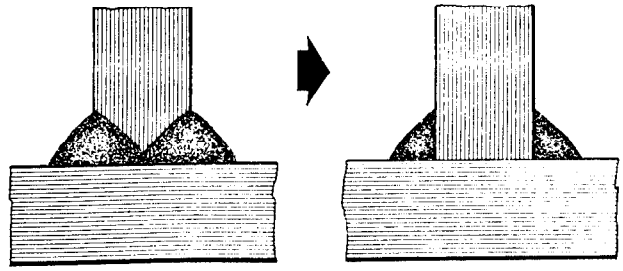


The modifications which can be made to reduce the risk of tearing in a T or cruciform joint are :

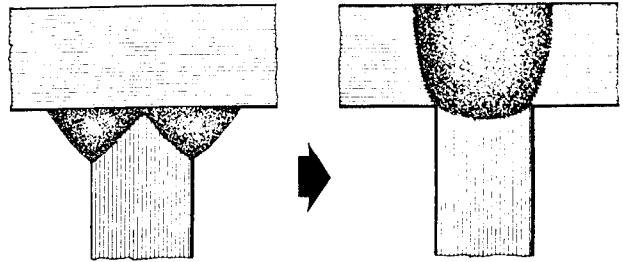
- 1 Replacement of a single-sided joint with a double-sided balanced joint.

This is only a marginal improvement caused by reducing the volume of weld metal in the joint and balancing the strains. The double-sided joint is still a risk situation.

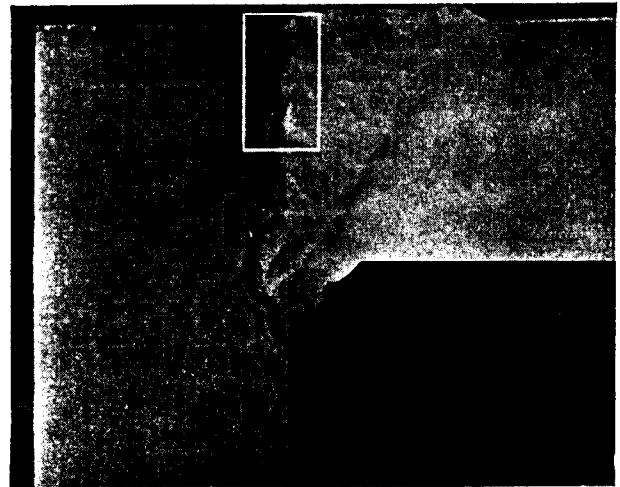
- 2 Replacement of full penetration butt welds with simple fillet welds. (This modification must take into account all other design requirements and may not be permissible.)



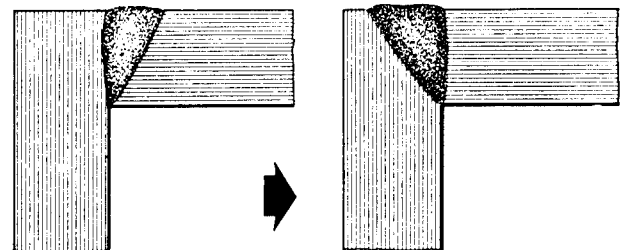
- 3 Redesign of a joint detail which virtually eliminates any risk of tearing by reorienting the weld fusion boundaries with respect to the plate surfaces. This modification is expensive and not always practicable, e.g. with cruciform joints. It has been used by about one-third of the fabricators who answered the questionnaire. In some situations electro-slag welding could be used to eliminate the risk without incurring too great a cost penalty.



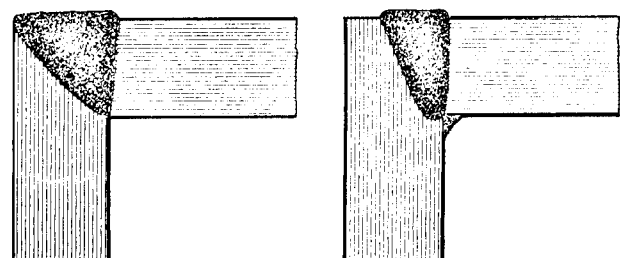
Corner joints. Corner joints are common in the single-sided form in box sections etc., and the double form in more complex fabrications. Cracking can occur on one or more planes through the plate thickness and is often visible or readily detected on the plate edge. The simplest method of reducing the likelihood of tearing in this type of joint is to modify the joint preparation by machining or cutting the bevel on the suspect plate. This technique is widely used but is not completely without problems. With large angle preparations the cost is high and large volumes of weld metal are used, but if small angle preparations are used there is still some risk of tearing if the plate is highly susceptible. The best compromise will involve choosing an economic procedure together with a small volume of weld and putting some preparation on the critical plate.

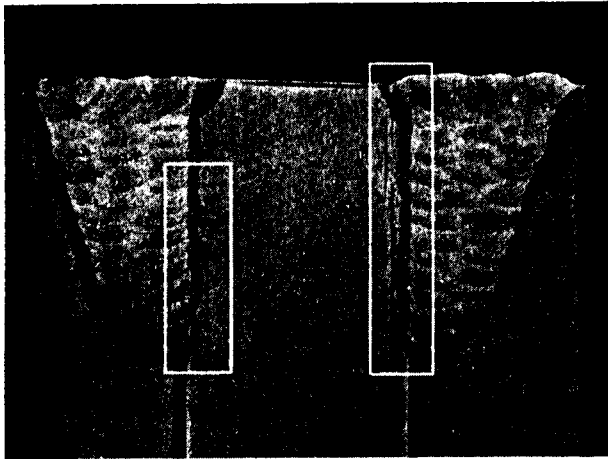


Modification of bevel to reduce risk



Left Large angle expensive
Right Smaller angle some risk





Double corner joint with single sided butt welds showing extensive lamellar tearing

Points to note

- 1 Be aware of joint details in potentially critical situations.
- 2 Change joint detail and/or weld preparation to reduce the risk of tearing.
- 3 Welds should not be larger than necessary. Welds which are too large increase the risk of tearing and are expensive.
- 4 Welds should be double-sided rather than single-sided, where practicable.
- 5 Large full penetration welds should not be used if smaller simple fillets are satisfactory *taking into account other design considerations.*

Butt joints. Lamellar tearing seldom occurs in conventional butt joints since the fusion boundary is at a large angle to the plate surface. However opening up of planes of inclusions caused by shrinkage strains in the ST direction has been reported on a few occasions.

Weld sizes

Much of the literature on lamellar tearing associates the problem with large welds, usually greater than about 20 mm in leg length; this figure applies to both fillet and butt welds. Instances are reported of tears associated with single- and two-pass fillet welds, but occurrences in such small welds are rare. In the questionnaire, just over half the replies considered that there was a minimum weld size below which lamellar tearing was not a problem. Of these replies about one-quarter put the critical length as less than 12 mm while about three-quarters felt it was 12 mm or above.

A number of replies to the questionnaire and authors in the literature have emphasised the fact that, although increasing leg length does increase the risk of cracking, restraint and weld metal volume are more important.

Materials

Steel type. No single grade of steel in the questionnaire was reported to give rise to significantly more tearing than any other. However there have been reports that aluminium-treated fully killed steels can be more susceptible than the corresponding silicon-killed grades of similar plate thickness not treated with aluminium. It should also be pointed out that there are steelmaking procedures involving the use of aluminium for deoxidation and grain refinement which result in steels with both low inclusion contents and very low susceptibilities to lamellar tearing. There are metallurgical reasons for these phenomena since aluminium treatment modifies the shape of both sulphide and oxide inclusions.

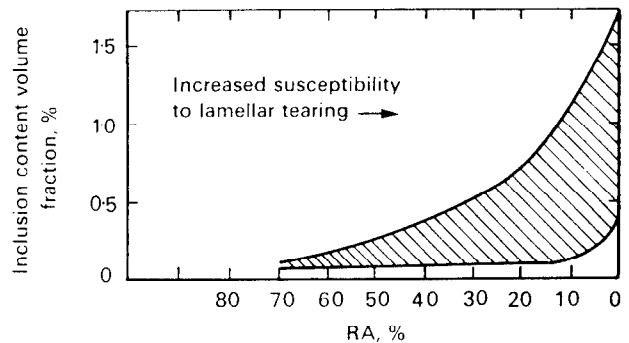
There are a number of instances of tearing in semi-killed steels and there is no evidence that these are inherently less susceptible than fully silicon-killed steels.

Steel strength level. In general, smaller defects become more significant with steels of increasing yield strength, and thus, for a given steelmaking practice and inclusion content, the ST ductility decreases for higher strength steels. However, for a given application, thinner plate is employed in the case of high strength steels, and flexure during welding will help to reduce the incidence of lamellar tearing in many structures. Nevertheless the questionnaire revealed that the incidence of tearing in high strength steels > 385 N/mm² yield strength appears to be higher than would be expected compared with the usage of lower strength steels.

Steel thickness. Lamellar tearing has been reported in plate thicknesses ranging from 10 to 175 mm. Because of the degree of deformation introduced into thin plates during rolling they can show poorer ST ductilities than thicker plate. However they do not necessarily exhibit a greater incidence of tearing, because flexure of the plate can occur limiting the strains in the ST direction. Exceptions to this have been reported in rolled plate nozzles and in cruciform joints made from thin plate, neither of which allow flexure to take place, and in these cases severe lamellar tearing has been encountered.

Most fabricators have experienced tearing in plates in the range 12 — 60 mm in thickness but the majority of these feel that there are few problems with plates below 25 mm in thickness.

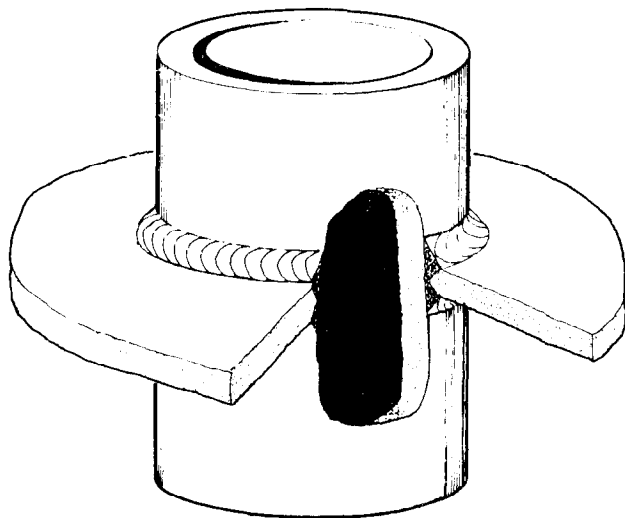
Steel cleanliness (inclusion content). Much work needs to be carried out to define precisely the relationships between inclusion content and the incidence of lamellar tearing. However a broad link has been established between inclusion content and the incidence of cracking. Any technique which can be used to reduce the inclusion content therefore increases the chance of freedom from tearing. Electric furnace steelmaking sometimes coupled with vacuum degassing can produce clean steels, and there have been reports of the successful use of these steels to overcome the problem.



Experimental relationship between ST %RA values and inclusion volume fraction

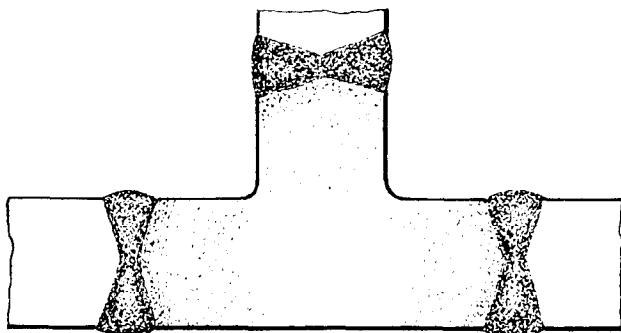
Points to note

- 1 No grade of steel can be singled out as being distinctly more susceptible than any other although there is some opinion and supporting evidence that aluminium-treated steels can have higher susceptibilities than corresponding silicon-killed grades not treated with aluminium and of comparable thickness, unless special care is taken during manufacture.
- 2 There can be an increased risk of tearing with increasing strength level.
- 3 Most reported occurrences of tearing are in plates greater than 25 mm in thickness, although thin materials (< 25 mm) can have poor ST properties.
- 4 Any steelmaking technique which reduces the inclusion content of the steel will reduce the risk of tearing.



Product type. Lamellar tearing is principally encountered in rolled steel plate and so any technique which allows the rolled plate to be replaced by some inherently less susceptible material can result in freedom from cracking.

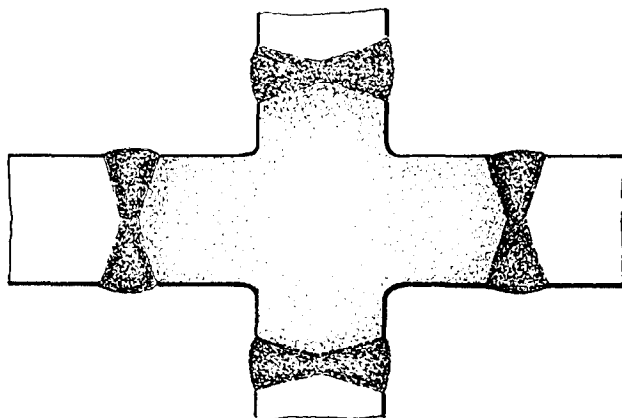
Forgings can be used to replace rolled plate nozzles and have been very successful in this type of application. The steelmaking route often employed for large forgings usually results in a cleaner steel and this, coupled with less deformation during production, generally results in a material of low susceptibility. In some instances 'bored-out' solid forgings can be used for nozzles. These have a very low susceptibility to tearing.



Castings and extrusions can be used to replace T or cruciform joints and by using butt joints virtually eliminate any risk of tearing.

However they are expensive and involve considerable extra welding. They tend to be used only in highly critical situations.

The reported success of this form of material selection and modification to joint design is high and ensures virtual elimination of the problem at a price.



Negotiation with steel suppliers. There are a number of stages during the steelmaking route where special precautions and selection techniques can be taken to ensure a product which is of better than average cleanliness and is therefore potentially less susceptible to tearing. For instance, it may be practicable to select certain slabs from an ingot which are expected to have better than average cleanliness and properties, and these may be suitable for certain critical applications or sites in critical structures.

The number of reported instances of direct negotiation with steelmakers is small but the success rate is fairly high and this approach is strongly recommended in the initial planning and design stages of structures where lamellar tearing would be both serious and expensive.

Ultrasonic testing of plate. Conventional pulse echo ultrasonic testing of plate for the detection of laminations and clusters of very large inclusions prior to welding is widely used. However the conventional techniques are not reliable for detecting potential susceptibility to tearing, since lamellar tears can arise at clusters of much smaller inclusions which would not normally be recorded with present ultrasonic techniques. Development work is in progress to evolve new NDT techniques capable of detecting the type and size of inclusions responsible for tearing.

The success rating of ultrasonics in detecting susceptible plate is at present very low but this does not mean that the present techniques should not be used for identifying laminated plate, since tearing could readily develop from laminations in many joints.

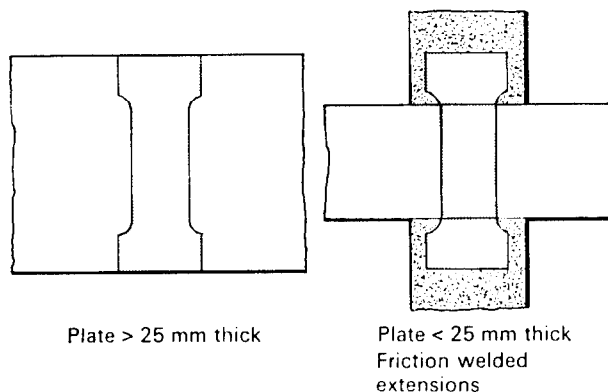
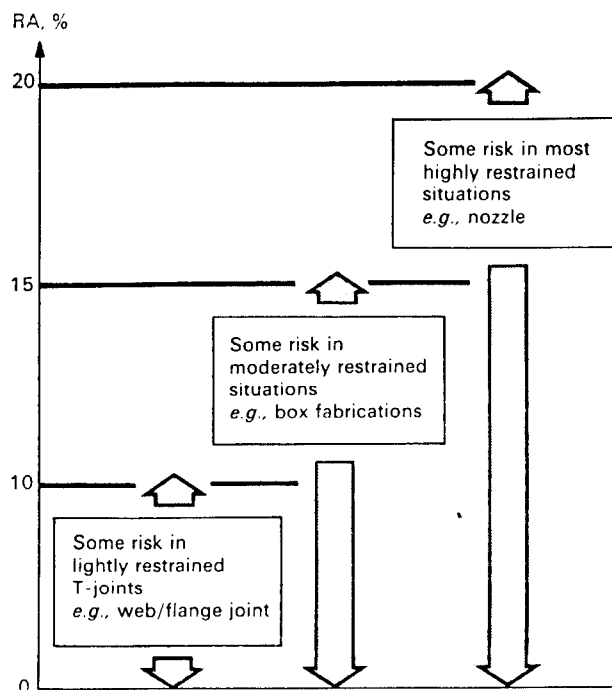
Destructive testing. It is only recently that sufficient data has become available to relate ductility measurements (% reduction in area) made on small scale ST testpieces with the incidence of tearing.

Where offcuts of plate, samples from manholes and holes for penetrators, etc. are available, ST tensile tests can be carried out to assess the risk of tearing. A number of problems have been described in the literature but the results of this type of test based on a cylindrical tensile specimen (6.4 mm in diameter) represent the best accumulation of relevant data to date. The major difficulties lie in the scatter of results within plates and in the fact that in most cases there is no guarantee that the area tested is representative of the area to be welded. Approximate limits appropriate to the incidence of tearing are given in the diagram.

Also shown are the procedures for extraction of the specimens from plates of varying thicknesses.

Other testing techniques are being considered and are under development but it will be some time before sufficient data will be available for their regular use in material selection.

Few fabricators have used this method of selection to date but the success rate with those that have is quite high.



Points to note

- 1 In critical structures, forgings, castings, or extrusions can occasionally be used and result in virtual elimination of lamellar tearing.
- 2 In the early planning and design stages of structures where lamellar tearing is potentially a serious problem it is advisable to consult the steelmaker. Steps can sometimes be taken to considerably lessen the risk of tearing.
- 3 Conventional pulse echo techniques although useful for detecting laminations in plate cannot reliably detect small inclusions which can give rise to tears.
- 4 Destructive testing using small-scale mechanical tests although at an early stage of practical application can be used for material selection.

Welding factors

The choice of welding process, consumables, parameters, and technique can influence the incidence of lamellar tearing. Their effects and the relative importance of these factors are discussed below. The information has been obtained entirely from discussions with fabricators and users and from completed questionnaires.

Welding process. Lamellar tearing has been encountered using most conventional processes, with the exception of electro-gas and electro-slag welding, which are not used for fillet welds and only rarely for T butt welds. Case histories exist of tearing associated with the manual metal-arc (MMA), gas shielded metal-arc (both CO₂ shielded and Ar/O₂ shielded) and submerged-arc processes. There appears to be a lower risk of tearing with the higher heat input processes, probably due to the greater width of the HAZs, the deeper weld penetration, and the associated smaller strain gradients. A second factor probably explaining this trend is that the weld deposits of the high heat input processes are generally of lower strength compared to, say, the MMA process, and this lessens the risk of lamellar tearing by allowing more strain to be accommodated in the weld metal than in the HAZ and in the parent plate.

Choice of consumable. The risk of lamellar tearing can be reduced by choosing electrodes or wires giving deposits of low strength, for the reason given above. Where mild steel consumables are being used for a structure, there is little scope for choosing a lower strength consumable, although consumables of the same type can vary in strength between manufacturers. However, the selection of mild steel consumables for critical joints where higher strength consumables would normally be used is occasionally a feasible procedure. Of eleven fabricators who reportedly tried this technique, six said it was particularly successful.

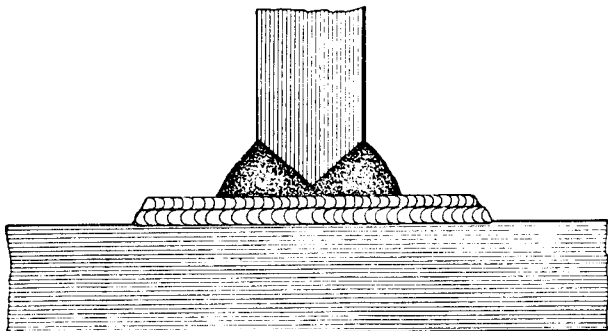
Welding conditions. Changes in heat input within a process and changes in preheat temperature have been found to have little effect on the incidence of tearing. Generally, fabricators have raised heat inputs to try to avoid cracking but this has not been very helpful, only one out of eleven reporting any success. However, there has been one instance where a small gauge MMA electrode was substituted for a larger gauge to produce a weld of reduced leg length and heat input, and tearing was avoided.

Of seventeen fabricators who have changed preheat temperatures, none reported any success. In fact, in one case an increase in preheat temperature was reported to increase the extent of tearing when applied locally at a nozzle connection.

Welding techniques. A number of welding techniques can be applied as precautionary measures in order to minimise the risk of tearing:

(a) Buttering

One or more layers of low strength weld metal deposited on the surface of suspect plate material is widely used as a precautionary technique. The submerged-arc process is commonly employed where feasible and the buttered layer should extend 15 — 25 mm beyond each weld toe and be about 5 — 10 mm thick. Eleven out of twenty-one firms reported



this technique as being particularly successful. In a very few instances tearing was reported as being caused by the buttering procedure itself.

In these cases, it was necessary to groove the parent material and butter, as shown in the accompanying diagram. The dimensions of the buttering layer should be approximately as before. Eleven out of eighteen firms found this technique beneficial. In effect, this technique is carried out when lamellar tears are repaired by gouging or by chipping out the cracked regions and rewelding.

(b) *In situ* buttering (*Bottom left*)

A modification of the buttering technique for which some success has been claimed (nine out of fifteen firms) consists of depositing a layer of weld metal on the suspect plate prior to completing the weld as indicated. The technique, in principle, relies on minimising the plastic strains in the parent material.

(c) Balanced welding (*Bottom right*)

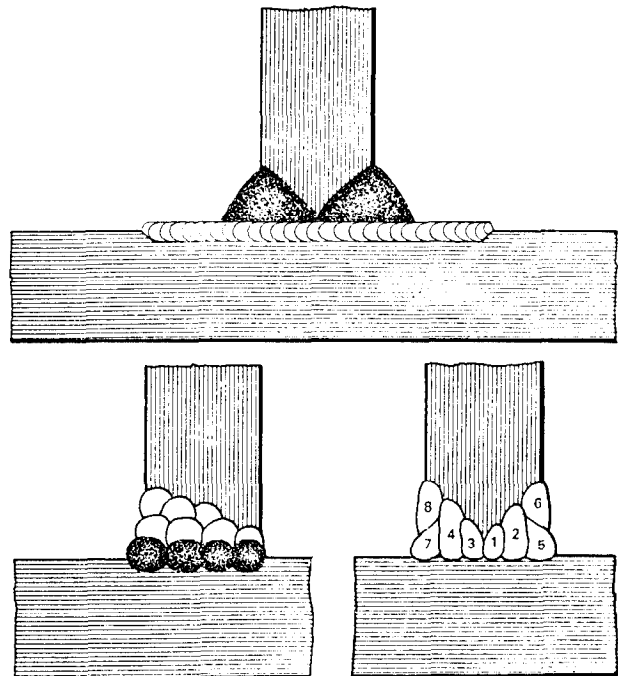
In T butt welds made with susceptible plate lamellar tearing initiating from the weld root can occasionally be prevented by filling up the two welds in a symmetrical manner, depositing several runs in one weld, followed by the same number in the second, and repeating the sequence. Of eighteen firms who have tried this technique, three reported success.

(d) Peening

Peening weld runs at intermediate stages during welding has been attempted in order to lower residual stresses and lessen the risk of tearing. No real measure of success can be claimed, with only one out of eleven reporting any improvement.

(e) Intermediate stress relief

Reduction of residual stresses by thermal means has been attempted by several fabricators. This has not been particularly successful, possibly because the thermal treatment by itself can increase the incidence of defect indications seen by ultrasonic techniques, as noted below.



Points to note

- 1 The choice of welding process has a minor effect on the incidence of tearing, although the risk appears to be less for the high heat input processes.
- 2 Within a process, changes in heat input and preheat have little effect on tearing unless the size of the weld is reduced at the same time.
- 3 Lower strength weld deposits are beneficial.
- 4 The techniques of buttering, grooving and buttering, and *in situ* buttering have a reported success rate of greater than a half.

DETECTION OF LAMELLAR TEARING AFTER WELDING

The following NDT methods are available. The potential problems associated with each are also listed :

| Method | Problems |
|-----------------------|---|
| Surface techniques | |
| Visual | Satisfactory for surface cracking but not for subsurface tears |
| Dye penetrant | |
| Magnetic particle | |
| Subsurface techniques | |
| Radiography | Orientation of tearing usually makes this impossible |
| Ultrasonics | Access is sometimes difficult. Problems of interpretation, but the <i>only possible method</i> for subsurface detection |

Ultrasonics is probably the most widely used technique but there may be problems in distinguishing true lamellar tears from inclusion bands and other forms of cracking. Cases are reported where ultrasonic indications had suggested cracking, whereas on sectioning or gouging prior to repair no cracking was found. It is possible that, in some cases, inclusions close to the weld had decohered from the matrix during welding and were responsible for an increased ultrasonic response. It is also believed that similar decohesions may take place during stress-relief heat treatments, which could be an explanation for the cases of apparent crack formation and growth detected by ultrasonics after such treatments. It is likely that a number of anomalous indications of tearing have been the result of the use of high probe frequencies and equipment gain settings. It has been reported that frequencies of 2 MHz are quite suitable

for the rapid location of true tears and that precise dimensions can then be fixed by the use of 4/5 MHz probes. It is also important to set up equipment gain and acceptance criteria so that clusters of inclusions and dense microstructural bands, which appear as defect indications, do not constitute rejectable defects.

It should be noted that there may be difficulties with highly attenuated signals from thick dirty plates.

If joints are to be closely examined after welding it is important to carry out a comparable survey in the region of the weld on the unwelded plate so that comparisons between the two can be made. These should be carried out on a grid system and accurate records retained for comparison thus enabling pre-existing indications to be distinguished from true lamellar tears.

Points to note

- 1 Make sure welding procedures are correct (by using joint simulation tests if necessary) and so eliminate any risk of confusion with other types of cracking.
- 2 In critical areas carry out a detailed survey of the plate prior to welding and record this. Retest after welding and so enable pre-existing defects (large inclusions etc.) to be distinguished from lamellar tearing.
- 3 Pay particular attention to the position of the cracking in relation to the plate thickness and weld fusion boundary, to avoid confusion with lack of penetration defects, entrapped slag, etc.