Assessing Toughness Levels for Steels to Determine the Need for PWHT

BY D. J. ABSON, Y. TKACH, I. HADLEY, AND F. M. BURDEKIN

Fracture mechanics calculations were used to determine toughness levels for C-Mn and low-alloy steels then compared to code recommendations regarding postweld heat treatment

Postweld heat treatment (PWHT) is applied to welded steel assemblies primarily to reduce the likelihood of brittle fracture. This is achieved through a reduction in the level of tensile residual stresses and through tempering of hard, potentially brittle, microstructural regions. There are, of course, economic and logistical incentives to avoid PWHT wherever possible.

This article reviews previous fracture mechanics methods used to form the basis of recommendations for fabrication codes, and outlines a generalized fracture mechanics approach to illustrate the implications, in terms of defect tolerance and toughness requirements, of not carrying out PWHT on welded steel structures. A series of curves is generated showing the relationship between material strength, material thickness, service temperature, and required impact properties.

The objective of this article is to demonstrate the use of fracture mechanics procedures to define minimum toughness requirements for welded fabrications so that PWHT is not needed.

Approach

Fracture mechanics calculations used previously as a basis for code recommendations have been reviewed, and further independent calculations have been carried out, based on the methods described in BS 7910:1999 (incorporating Amendment Number 1) (Ref. 1). The assessment was implemented using TWI's *Crackwise 3* software (Version 3.13).

Example calculations were carried out to determine the minimum required material fracture toughness for a variety of cases, in order to define limits for the avoidance of PWHT. However, it should be noted that the results of the calculations are intended to demonstrate the principle of analysis procedures such as BS 7910 for justifying the avoidance of PWHT, and to illustrate the trends in toughness requirements with variables such as material strength and thickness. For a particular structure, the actual requirement may be higher or lower than that shown in this article, depending on factors such as the actual stress applied to the component, the presence of areas of stress concentration, and the effectiveness of nondestructive examination (NDE). The results of this study should, therefore, not be applied directly to actual fabrications without expert consideration.

The Use of Fracture Mechanics in Assessing the Need for PWHT

Justification for Considering a Fracture Mechanics Approach

While limiting thickness criteria beyond which PWHT is required have been

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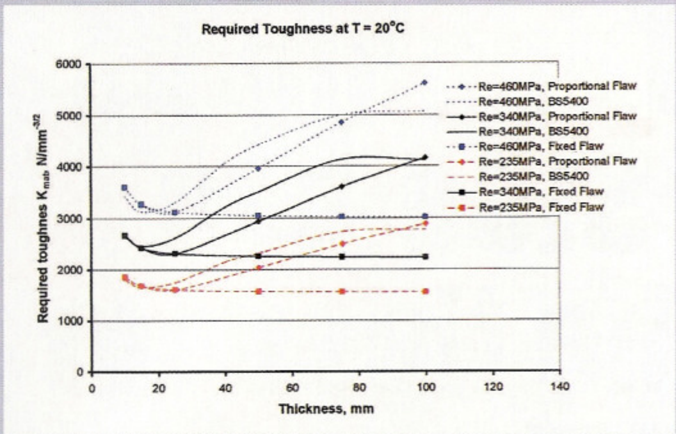

Fig. 1 — Results from fracture mechanics analyses for proportional and fixed flaws, and a comparison with BS 5400 requirements.

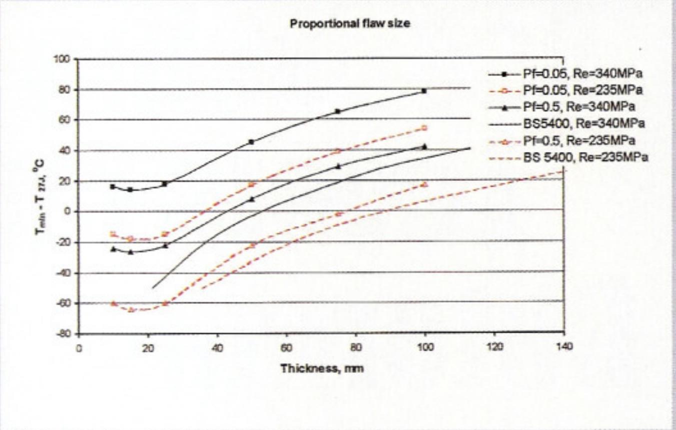

Fig. 2 — Minimum toughness requirements for exemption from PWHT, plotted as ($T_{min} - T_{27J}$); proportional flaw assumed.

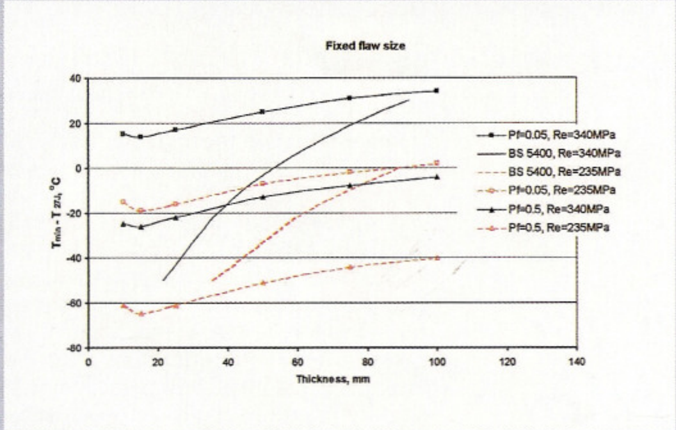

Fig. 3 — Minimum toughness requirements for exemption from PWHT, plotted as ($T_{min} - T_{27J}$); fixed flaw size assumed.

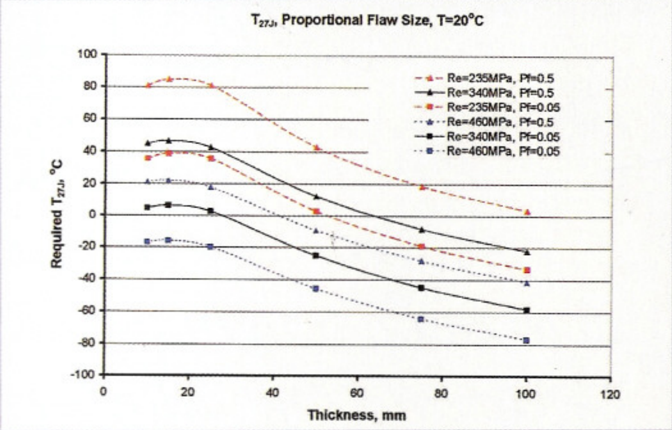

Fig. 4 — Minimum toughness requirements for exemption from PWHT, plotted in terms of required value of T_{27J}, T_{min} = 20°C, and proportional flaw size assumed.

in use for many years for pressure vessels and piping, and can be considered to have been validated by custom and practice, the scientific derivations of these criteria may not always be known. In the United Kingdom, the original requirements for low-temperature applications of pressure vessels and storage tanks were based on an extensive series of notched and welded wide plate tests carried out at The Welding Institute (TWI) in the 1960s (Ref. 2). However, it is likely that the criteria for many other codes were devised on the basis of engineering experience and best practice at the time. The basis on which the criteria were derived may not be so relevant today, owing to various factors. For example,

- Steelmaking technology and welding consumables manufacture have improved considerably in the last 25 to 30 years. As a consequence, the fracture toughness of base steels and welds has improved.
- Improved understanding of welding defects has enabled the development of improved welding procedures and methods.
- Knowledge of welding residual stresses and the influence of these stresses and material thickness upon the fracture event (through fracture mechanics) has improved.
- Nondestructive testing methods have improved since the derivation of some of the codes. For example, ultrasonic inspection has been widely used as a regular inspection tool only in the past 25 to 30 years. Prior to this, radiography (a technique that is not well suited to the detection of planar flaws) would often have been the main technique used to identify embedded defects.

An alternative approach for deciding whether PWHT is necessary to avoid failure by fracture is by conducting a fracture mechanics assessment of the as-welded joint, using a recognized procedure such as that described in BS 7910 (Ref. 1). It is obvious that a criterion for PWHT based on a fracture mechanics assessment is more complicated than a criterion based on material thickness alone. Nevertheless, the use of a fracture mechanics method is an attractive option to determine whether PWHT is necessary for the avoidance of failure by fracture.

A fracture mechanics analysis essentially provides a relationship between stress levels (applied and residual), flaw sizes, and material properties (fracture toughness and yield strength). In determining whether PWHT is required, assumptions have to be made about stress levels and the size of flaws that might escape detection during inspection. The toughness level required to avoid failure can thus be determined.

Fracture mechanics-based procedures have been used previously as the basis for determining maximum thicknesses for as-welded construction in the U.K. bridge and building codes (Refs. 3, 4), and also for the Eurocode 3 requirements. Details of these requirements were discussed in a previous article (A Review of Postweld Heat Treatment Code Exemptions, *Welding Journal*, March 2006, pp. 63–69).

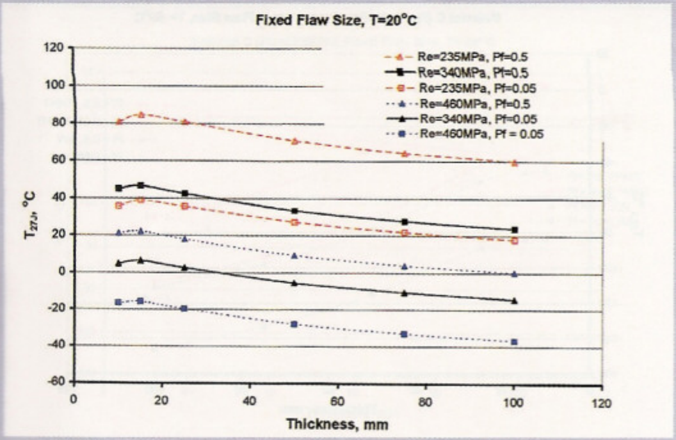

Fig. 5 — Minimum toughness requirements for exemption from the PWHT, plotted in terms of required value of T_{27J}, T_{min} = 20°C, and fixed flaw size assumed.

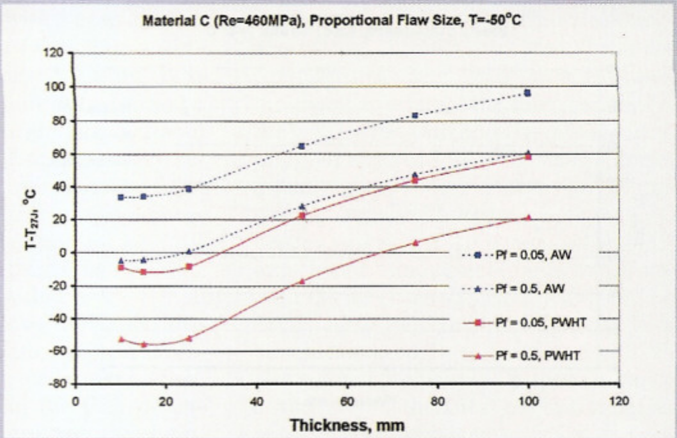

Fig. 6 — Minimum toughness requirements for a high-strength steel (R_e = 460 MPa), plotted as ($T_{min} - T_{27J}$); T_{min} = –50°C and proportional flaw size assumed.

The Influence of Increasing Wall Thickness on the Measured Fracture Toughness of C-Mn Steels

The basic assumption of fracture mechanics analyses is that fracture will occur in a material when the crack tip driving force, i.e., the applied stress intensity, exceeds the material's resistance to fracture initiation, i.e., the fracture toughness of the material.

So far as the crack tip driving force is concerned, the total applied stress intensity, $K_{I,Total}$, depends on both the applied stress intensity and the stress intensity due to residual stresses resulting from the welding process. Hence, this factor can be expressed as

$$K_{I,Total} = K_{I,Primary\ Stresses} + K_{I,Residual\ Stresses}$$

Higher levels of stress triaxiality in thicker sections render them more susceptible to fracture. For these reasons, the reduction of residual stress levels in thicker components by PWHT may be necessary, in order to reduce the likelihood of brittle fracture.

Regarding materials' resistance to fracture, it is generally observed that the measured fracture toughness of a ferritic steel tested in the lower transition region decreases with increased thickness of the specimen being tested. In the case of a through-thickness crack (for example, in the case of fracture mechanics test specimens), this phenomenon can be explained in terms of two factors.

1. Weakest link theory. The likelihood of a crack front sampling a region of low toughness increases with the amount of material it samples. That is, the average measured fracture toughness is expected to decrease with increased crack front length.

2. Crack tip constraint. The fracture process is also highly dependent on crack tip constraint (triaxiality), which in turn is a function of the geometry of the specimen being tested, including specimen thickness, loading mode, and crack depth. (The last two variables are usually standardized in fracture mechanics testing.) As the thickness of a SENB (single edge notched bend) specimen increases, so a greater proportion of the crack front experiences high crack tip constraint, and the fracture toughness decreases, until in the limit the plane strain fracture toughness, K_{Ic}, is reached.

Engineering Critical Assessment Based on a Fracture Mechanics Approach

Analyses Used as the Basis for BS 5400:2000 and BS 5950:2000

The basis for the original requirements of BS 5400 (Ref. 5) for bridges and the related requirements for BS 5950 (Ref. 6) for buildings in the early 1980s is given in Ref. 3. The requirements were based on a combination of existing experience, the results of notched and welded wide plate tests, and a framework based on a fracture mechanics analysis using the then current edition of BSI Document PD 6493 (which subsequently became BS 7910 (Ref. 1)).

The assumptions about initial flaw sizes and applied and residual stress levels have a strong influence on the resulting calculated requirements for fracture toughness. These then have to be related first to limiting thickness conditions and second to Charpy test requirements. For most practical applications of welded structures and pressure-related components, toughness requirements are expressed in terms of the Charpy V-notch impact test. Therefore, if fracture mechanics methods are to be used, it is also necessary to have available a relationship between fracture mechanics-based toughness and Charpy test energy absorption.

As a result of the development of improved correlations between fracture mechanics toughness and Charpy energy absorption (Ref. 7), updated fracture mechanics treatments from PD 6493 to BS 7910 and the need to improve the treatment for typical stress concentration regions, a collaborative project was undertaken in the late 1990s between TWI and UMIST. The results from this project were used as a background for revised requirements for the avoidance of brittle fracture in BS 5400:2000 and BS 5950. Examples of the results from these previous analyses are compared with those derived in the present work in Figs. 1–3, and discussed in the Fracture Mechanics section of the Discussion.

New Calculations Carried out in the Present Work

Example calculations were carried out in the present project, independently of the work described in the previous section, to determine the minimum material fracture toughness for a variety of cases, in order to define limits for the avoidance of PWHT. The starting assumptions for the analysis were somewhat different from those described in the previous section, as summarized in Table 1. The model used to calculate the necessary material fracture toughness was based upon a semielliptical surface-breaking flaw in a flat plate of thickness B. Note that the results of the calculations are intended to demonstrate the principle of analysis procedures such as in BS 7910 (Ref. 1) for the avoidance of PWHT. The findings should not be applied directly to actual fabrications without expert consideration.

For the fixed flaw size case, the equivalent figure would be –37°C. For a probability level of 0.5, the corresponding figures are –41° and 0°C.

Since the height of the proportional flaw is assumed to be 0.1 times the thickness, the above proportional flaw size calculation assumes the existence of a surface flaw of 10-mm through-wall height and length 100 mm. The fixed flaw size case assumes that a surface flaw 3 mm high and 30 mm long could be present in the structure (and could be missed by nondestructive examination). In practice, whether or not PWHT is required would therefore depend in part on judgments about the size of flaw that could be reliably detected, and the probability figure considered appropriate. For example, the figure $P_f = 0.4$ for the BS 5400: Part 3 rules was chosen largely on the basis of fitting existing service experience of the avoidance of fracture failures, with particular reference to bridge failures.

It should be noted that steels with strength $R_e = 460$ MPa can be supplied with excellent Charpy properties, and the use of 100 mm thickness at 20°C in the as-welded condition is therefore possible, subject to the specification of appropriate Charpy energy and NDE.

Equivalent calculations can be carried out for $T_{min} = -50°C$, using Figs. 2 and 3. Since $T_{min} - T_{27J}$ is virtually independent of T_{min}, the T_{27J} requirements shown above for $T_{min} = 20°C$ simply shift by the change in minimum service temperature, i.e., by 70°C. Consequently, the requirements for a high-strength ($R_e = 460$ MPa) 100-mm-thick section steel shift to $-147°C < T_{27J} < -111°C$ (proportional flaw assumption) or $-107°C < T_{27J} < -70°C$ (fixed flaw assumption). Given such onerous requirements on Charpy energy, PWHT may be the only option for thick-section, high-strength steels operated at low temperature (for example, pressure equipment under blow-down conditions).

An additional analysis was carried out to investigate and illustrate the influence of PWHT on the estimated minimum requirements of the material toughness to avoid failure by fracture. The method used was similar to that used for the as-welded state, except that the magnitude of secondary (residual) stress was assumed to be 20% of the yield strength of the base material, as recommended by BS 7910 (Ref. 1).

The minimum required fracture toughness, temperature T_{27J} and values of ($T_{min} - T_{27J}$) were calculated for material C (high-strength steel) in the as-welded condition (AW) and after PWHT. The results, given in Figs. 6–9, reveal a large reduction in fracture toughness requirements for the material after PWHT. For example, the required minimum fracture toughness for a section thickness of 100 mm (proportional flaw size) decreases from 5500 $N/mm^{-3/2}$ in the as-welded condition to 3000 $N/mm^{-3/2}$ after PWHT. In terms of Charpy requirement, the values of ($T_{min} - T_{27J}$) shift by approximately 38°C (50°C for the fixed flaw assumption).

Discussion

Fracture Mechanics Assessment

As noted earlier, the required fracture toughness (K_{mat} values) for a thick-section welded joint made from high-strength steel was found to approach 5500 $N/mm^{3/2}$ (173.8 $MPa\sqrt{m}$) at the minimum operating temperature. This requirement may be somewhat difficult to satisfy in the weld and heat-affected zones of many structural steels without careful control of welding consumables and procedures, particularly as fracture toughness is generally observed to decrease with both section thickness and material strength.

As material yield strength increases, not only do specified toughness levels commonly increase, but it becomes increasingly difficult to meet toughness requirements without PWHT, as noted earlier. For example, for steel C ($R_e = 460$ MPa) 25 mm thick, intended for service at –50°C in the as-welded condition, the results of the fracture mechanics model calculations show that, for a failure probability $P_f = 0.05$, $T_{27J} = -89°C$ is needed. This would probably be impossible to achieve in a base and HAZ of a C-Mn steel of this strength. It may be noted that, for the example given, the PD 5500 (Ref. 26) toughness requirement would be 40 J at –76°C ($T_{27J} \approx -185°C$), while the API 620 (Ref. 19) requirement would be 40 J at –67°C ($T_{27J} \approx -76°C$). Thus, while the requirements of the codes have generally been found to be conservative, the degree of conservatism clearly varies, and may not always be present for the higher-strength grades of steel. For fine-grained C-Mn steels of this strength level that are intended for service at low temperatures, it may therefore be appropriate to carry out a fracture mechanics analysis to see whether PWHT can be safely omitted.

The fracture mechanics calculations have generated graphs that give some pointers to areas where existing code requirements are too restrictive, and also some indication that PWHT would be appropriate where it is currently not required. It may be possible to assemble available compositional, toughness, residual stress, and welding data from TWI and other databases, in order to generate similar families of curves, based on measured data. Preliminary graphs could be used to identify significant gaps for which a program of testing could be drawn up. By using such graphs, individual applications could then be considered, using material toughness and material thickness, carbon equivalent, and minimum welding parameters to demonstrate the case for the omission of PWHT or for increases in the limiting thickness. It will, of course, be necessary to convince insurance companies and classification societies involved with the plant or structure of the viability of this approach, and it is therefore desirable that they are involved in any discussions from the outset of the work.

In the present investigation, it has been confirmed that a fracture mechanics assessment, with assumed values of defect size and material strength, provides a cost-effective method of investigating whether PWHT is necessary in order to avoid failure by fracture. The cost of performing the analyses is relatively modest and, in some cases, the costs saved if PWHT can be avoided are large.

The strength of the welds considered in the calculations contained in this article were assumed to be matched to that of the base materials. In practice, welds are usually designed to slightly overmatch the base material properties. In this case the residual stresses in the direction parallel to the weld bead are expected to be higher than the yield strength of the base material. The adverse effects this has upon the critical toughness may be partially accounted for by the increased strength of the weld metal. The effects of weld overmatching (or undermatching) are worthy of more detailed consideration on a case-by-case basis.

General Discussion

While fracture mechanics analyses such as in this article and those carried out as a basis for BS 5400/BS 5950 and by Mohr (Ref. 8) can give an indication of what changes in the codes it may be possible to justify, the elimination of any anomalies can only be brought about when adequate toughness data become available. This is clearly one area where an irksome restriction exists, and where a program of welding and mechanical testing would demonstrate whether any changes should be made in the relevant specifications. Another approach is, with the agreement of all interested parties, to carry out a fracture mechanics assessment on a case-by-case basis. As noted in the earlier article, with this approach, Leggatt et al. (Ref. 9) showed that, in some of the examples they considered, PWHT was not necessary.

Conclusions

BS 7910 level 2 assessments have bee

carried out for two values of material design minimum temperature, using assumed values of material strength, flaw size, and stress. The BS 7910:1999, Annex J, correlation between fracture toughness and Charpy impact energy was used to derive toughness requirement in terms of T_{27J}, and the results have been compared with previous fracture mechanics-based analyses, including those underpinning the current BS 5400: Part 3 rules for fracture prevention in steel bridges. From this study, the following conclusions have been drawn:

1. If it is required to make a case for exemption from specific code requirements for PWHT, it may be possible to do so on the basis of a fracture mechanics analysis for a particular case. Such an approach will require consideration of the fracture toughness at the minimum service temperature, the quality of fabrication in terms of maximum sizes of flaw likely to be present, and the maximum stress levels (applied and residual) that will occur.

2. Fracture mechanics analyses carried out in the present work have been compared with those used as a basis for the general structural code requirements, and have given comparable results.

3. In a fracture mechanics assessment with assumed values of defect size and material strength, as expected, the toughness requirement can generally be expressed as a function of the difference in temperature between the material design minimum temperature (T_{min}) and the temperature at which the Charpy energy is at least 27 J. The toughness requirements become more onerous with increasing material strength and, more especially, with increasing thickness when the initial flaw size is assumed to be proportional to the thickness.

4. As examples, for T_{min} = 20°C, the toughness requirements are not unduly onerous, given the quality of modern steels and weldments, and the calculations provide an example where there is some justification for increasing the thickness limit beyond which PWHT is required in current codes.

5. For T_{min} = –50°C, the toughness requirements are sufficiently onerous that it might be appropriate to give a PWHT, even at the lower levels of thickness, for the higher strength grades. Possible examples are quenched and tempered steels, in certain applications, where the toughness may be inadequate at low design temperatures.

6. The required fracture toughness (K_{mat} values) for a high-strength, thick-section welded joint was found to approach 5500 N/mm$^{3/2}$ (173.8 MPa$\sqrt{m}$). This requirement may be somewhat difficult to satisfy in the weld and heat-affected zones of many structural steels without careful control of welding consumables and procedures, particularly as fracture toughness is generally observed to decrease with both section thickness and material strength.◆

References

1. BS 7910:1999, *Guide on Methods for Assessing the Acceptability of Flaws in Metallic Structures*, incorporating Amendment 1, now superseded by BS 7910:2005: *Guide on Methods for Assessing the Acceptability of Flaws in Metallic Structures*.

2. Woodley, C. C., Burdekin, F. M., and Wells, A. A. 1964. Mild steel for pressure equipment at sub-zero temperatures. *British Welding Journal* 11(3):123–134.

3. Burdekin, F. M. 1981. Materials aspects of BS5400: Part 6, paper 4 in *The Design of Steel Bridges*, Eds. K. C. Rockey and H. R. Evans, Granada ISBN 0 24611339 1.

4. Ogle, M. H., Burdekin, F. M., and Hadley, I. 2003. Material selection requirements for civil structures. *Proc. IIW Int. Conf. on Welded Construction for Urban Infrastructure*, 56th Annual Assembly of the IIW, Bucharest, Romania, Ed. D. Dehelean, International Institute of Welding, pp. 201–229.

5. BS 5400-3: 2000 (incorporating Corrigendum 1). *Steel, Concrete and Composite Bridges*, Part 3 — Code of practice for design of steel bridges.

6. BS 5950-1:2000. *Structural Use of Steelwork in Building*. Code of practice for design — Rolled and welded sections.

7. Wallin, K. 1994. New improved methodology for selecting Charpy toughness criteria for thin high-strength steels. IIW Document X-1290-94.

8. Mohr, W. C. 1997. Fracture mechanics to justify the minimum thickness for PWHT: Girth butt-welded steel pipe. Edison Welding Institute Report for Research Members MR9708.

9. Leggatt, R. H., Muhammed, A., Smith, A. T., and Cheaitani, M. J. 1999. Using fracture mechanics to claim exemption from PWHT — Four case studies. TWI Report for Research Members 679/1999.

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