CTOD AND WIDE PLATE TESTING OF WELDS WITH PARTICULAR EMPHASIS ON MIS-MATCHED WELDED JOINTS

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The subject of strength mis-matching effects on structural weldments fracture characteristics and structural performance has recently received great attention world wide. The mechanical heterogeneity of welded joints is generally not considered in current design practice, fracture toughness testing and defect assessment procedures. These methodologies have been established to provide safe structural performance based on conservative approaches and assessment routes by ignoring certain factors (such as weld strength mis-match) which can be important for the accuracy of fitness-for -service assessment procedures.

There are no strength mis-match effects in the linear-elastic regime if elastic modulus and Poisson`s ratio are the same for the weld and base metals. In the plastic regime, strength mis-match influences the straining capacity, limit load analysis and hence fracture characteristics of welds by altering the plasticity development pattern (i.e alteration of the proportion of remotely applied strain which reaches the crack tip) in the welded specimen from that characteristic of a cracked plain specimen. This redistribution of plasticity has significant influence on the wide-plate and CTOD testing and on the implications of these tests with respect to the structural assessment of welds. The aim of this paper is to give an overview of recent developments in the research on weld strength mis-match effects on fracture characteristics, CTOD and wide-plate testing of structural weldments.

INTRODUCTION

It is common practice to deposit weld metals which display higher strength (overmatching) than the steels used in various engineering structures. By doing this, a beneficial shielding effect of the higher yield strength weld metal (defective region in most cases) on a defect from imposed strains can be expected. Both strength and toughness properties of the defective region (weld joint) of any structure will clearly dominate the structural performance. The failure behaviour of the structure associated with this defect will certainly be *influenced* by the strength levels of the neighbouring zones. In other words, the straining capacity of a weldment not only depends on local toughness, but equally on the difference between the weld and base metal yield strengths, weld size, the yield to tensile ratio and defect size. Conventional designs for engineering structures with welded components do not directly address the weld metal yield strength mis-match and strain hardening effects on weld joint performance.

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Various studies [1-16] have addressed the fracture behaviour of mismatched weld joints and the results show that strength mismatch can significantly affect deformation and fracture behaviour of the welded joints under bending and tension loading. Therefore, strength mismatch has a strong influence on both applied and material toughness parameters based on the fracture mechanics parameters (CTOD or J-integral) in bend and tension loaded specimens. The effect of the relative difference (***mis-matching***) of the yield strengths of the base, weld metal and HAZ parts on defect assessment procedures and on toughness values (CTOD and J) of the material displaying a defect must be determined. Present defect assessment procedures are based on homogeneous materials and generally assume that defects occur in material of uniform mechanical and microstructural properties. In reality through the mechanical heterogeneity of welded joints influences structural behaviour. This effect, however, is not considered in these procedures. Therefore, there is still a need to establish a relationship between applied strain, toughness and defect size for mis-matched welds.

It is still difficult to define the optimum combination of weld metal strength and toughness for a given defect size, location (WM or HAZ) and application, since toughness decreases with increasing yield strength. It is now known that a complete fracture characterization of mismatched weld joints should not only be based on the mis-match ratio, $M = \sigma_Y^{WM} / \sigma_Y^{BM}$. This will lead to an oversimplification, since the effect of work hardening of weld and base metals is found to be even more important. Therefore, careful consideration should be given to various parameters such as; M, strain hardening exponents of the base material (n_b) and weld metal (n_w) as well as to the applied stress/strain range, weld metal width (2H) and relative crack size, 2H/(W-a) for the fracture behaviour analysis of under- and overmatched weld joints.

The goal of this paper is to give an overview of the recent developments in the examination of weld strength mis-match effects on the fracture characteristics, CTOD and wide-plate testing of structural weldments. However, it is a challenging task to cover a large amount of studies conducted recently within the limited available space of this manuscript. For further information, readers are asked to refer to the proceedings [17] of the first international conference *MIS-MATCH'93* for a wide-range of studies (53 papers) on the fracture characteristics of bonded bi-material joints and strength mis-matched welds. Furthermore, the International Institute of Welding (IIW) sub comm. X-F "weld mis-match effects" has recently started to work on this topic and its first meeting was held in Paris, April 1994 to discuss new developments in this area. Fourteen new IIW documents [18-31] have been presented during this meeting.

TENSILE TESTING OF TRANSVERSE WELDS

When it comes to tensile testing of whole mismatched weld joints in a transverse direction by using either flat or round tensile specimens, there can be a problem of verifying (quantitatively) the soundness of the weld deposit because of the difference in strength and ductility existing between base and weld metals. This strength mismatch will result in a failure in the lower strength base metal (overmatching case) even though the weld metal might contain defects. Although a fracture in the base metal can be considered acceptable, a true evaluation of weld metals is not possible under such circumstances. A complete picture of the strength level and its variation within the weld volume of the multi-pass structural weld metal should be determined by using "all-weld-metal" tensile specimens. It is known that root passes of many welds exhibit higher strength than the top side of the weld deposits. Such a local variation in mechanical properties induces further strength heterogeneity (mismatch) to be considered.

Nominally identical applied stress/strain levels cause different amounts of strain concentrations in the respective parts of the weld joints depending on the strength level of the weld metal, crack size and weld geometry. If the weld metal yield strength is greater than that of the base metal (overmatching) plastic straining can occur in the base metal (e_{BM}), while the weld metal remains in the elastic regime (e_{OM}) as shown schematically in Figure 1. Lower weld metal yield strength than the base metal (undermatching) will cause a concentration of the strain in the weld metal (e_{UM}) and local ductility of the undermatched weld metal will be exhausted prior to the onset of Gross Section Yielding, GSY. In this case the undermatched weld metal requires higher fracture initiation resistance (toughness) to prevent the risk of unstable fracture.

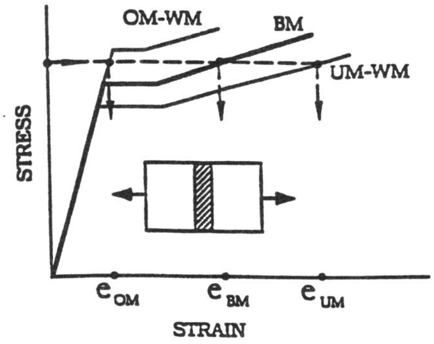


Figure 1. Schematic σ-ε curves of a transverse weld joint, showing development of different level of strain on under- and overmatched welds for a given stress.

GEOMETRIC EFFECTS ON YIELDING BEHAVIOUR OF WELDS

Geometrical mis-match

The yielding behaviour of weldments can be affected by geometrical mis-match between the two welded plates. A loss of strength and an increase of stress concentration will occur as the offset distance or misalignment increases. In fact, misalignment creates an in-plate bending moment. The resulting stress raising action may be detrimental to a low yield strength weld metal.

Weld reinforcement

Weld reinforcement is a beneficial factor for statically loaded weldments. Weld reinforcement gives an increase in the cross section of the weld deposit which increases transverse strength. Weld reinforcement might transfer the locus of failure from the weld metal area to the base plate. For example, the root and cap weld reinforcements of an undermatching weld metal in thin plate can shield, just like in the case of weld metal yield strength overmatching, the weld metal from (severe) plastic deformations.

Weld metal width (2H)

The weld metal width (perpendicular to the weld axis) -plate thickness (2H/B) and 2H to uncracked ligament (2H/W-a) ratios affects weldment deformation behaviour. Experiments on undermatched narrow gap weldments undertaken by Toyoda and Satoh [32] have shown that the overall straining capacity increases when the weld metal width is smaller than the plate thickness (2H/B<1). As pointed out by Kirk and Dodds [12], reducing weld metal width also elevates the stress for plastic flow but this effect cannot prevent weld metal strain concentration in the event of weld defects. In this case, weldment straining capacity for undermatching weldments can be low when weld metal or HAZ discontinuities occur [33, 34]. According to the study conducted by Petrovski and Koçak [34] that for a given weld metal yield strength and defect size, the plastic collapse load of the 26% undermatched weld (containing weld metal surface crack) was significantly higher than the 6% overmatched welds. However, plastic straining capacity of the undermatched welds was significantly lower than the base plate and overmatched weld panel.

The effect of weld metal width, 2H, on CTOD and J has been studied at various institutes. The results of the FE analysis conducted by Bingsen et al [2] on the sandwiched hard weld layer containing a centre crack, suggest that driving force (CTOD and J) will increase with decreasing H/a ratio and this effect was found to be significantly high at high load range. From the structural integrity point of view, they concluded that a crack in the hard and narrow region of a welded structure propagates more easily and consequently is more dangerous. Dong and Gordon [6] have reported similar findings by mentioning the independence of J parameter from H at low loads until the development of plasticity at the bimaterial interface (mismatch effect) within the base metal. From that point on, a rapid increase of J with decrease of H was observed on center cracked tensile (CCT) specimens. The FE results of Zhang et al [4] also suggest that if the ratio of H/(W-a) is larger than 1.0, the weld metal strength mismatching has no effect on the fracture parameters of the weld metal. According to their study, plates behave as if made entirely of the base metal, if the crack size is much larger than the weld width (a >> H).

Recent numerical and analytical slip-line analyses of the mis-matched welds carried out by Hao et al [35] clearly revealed the effect of the 2H/(W-a) on the yield load calculations of the wide-plates with transverse welds. Further, this work has been extended [30] in order to include the effect of constraint (i.e plate thickness effect, B/H) on the slip-line field development and hence on the yield load estimates. Influence of the geometry/width of the cracked weld metal has also been considered by other researchers [36-40] in the analysis of J and limit load calculations for mis-matched welds. Thus, all these studies clearly indicate that weld width (2H) has a significant effect on the plasticity development and hence on the driving force parameters of welds.

FRACTURE TOUGHNESS TESTING

Charpy-V Notch Impact Tests

The commonly used Charpy-V test is considered by many standards, codes and specifications as a quick and relatively inexpensive quality control test. The vast amount of data accumulated with this test method induces its continued use. However, this test leads to significant difficulties when applied to quantitative toughness measurements on welds or bi-material joints. High Charpy energy which includes the energy to initiate a crack and propagate to fracture does not necessarily mean that the weld joint or bi-material interface has adequate fracture resistance to fracture. The insensitivity of this test to detect the low toughness CGHAZ region (where weld integrity is generally the most questionable) is inevitably due to its large crack tip radius and propagating crack (deviated from original microstructure), both surely sampling mixed microstructures.

Obviously, the use of this test for determining the toughness of mis-matched weld joints and bi-material interfaces does not provide technically meaningful results. Significant crack path deviation occurs towards the softer part (weld or base metal depending on the mis-match level) of the specimens notched in the HAZ of conventional and narrow laser or electron beam welds. As a result, toughness data provides artificially decreased or enhanced values which do not represent the toughness level of the targeted region. Additionally, the toughness values can show considerable scatter and hence interpretation cannot be conducted in a straightforward manner. Furthermore, for a wide range of structural steel welds no generally applicable correlation between Charpy-V and CTOD has yet been found.

Healy and Billingham et al [41] have studied the effect of mismatching on Charpy-V transition toughness of the CGHAZ of high strength steel welds by using three weldments corresponding to M ratios of 0.8, 1.1 and 1.3. In the case of overmatched welds, for the HAZ notched specimens the crack propagation preferentially occurred in the lower strength (but tougher) base plate irrespective of test temperature. Such observations invalidate the widely held notion that the crack will follow the lowest energy path or most brittle path available. Their study has conclusively shown that this is not the case for the HAZ of strength mis-matched weldments.

CTOD and J testing of mis-matched welds

It is well established that elastic-plastic fracture mechanics parameters like Crack Tip Opening Displacement (CTOD) and J-integral are the most viable fracture parameters for characterizing crack initiation, growth and instability. Therefore, both parameters have been widely used to assess the structural integrity of cracked structural components and to select the suitable material for the given design requirements of the structural component of interest. The present fracture toughness testing procedures are basically developed for homogeneous metallic materials and generally assume that defects occur in material of uniform mechanical/microstructural properties. However, in reality, the mechanical heterogeneity of the weld joint will influence the plastic zone development and stress state at the crack tip and hence affect the obtained standardised fracture toughness parameters (CTOD or J). The use of present standards for the testing of welds and bi-material joints requires significant modifications on specimen preparation, testing and evaluation of the CTOD and J. Figure 2 shows some of the factors to be considered for testing of SENB specimens for testing of weld metal and HAZ regions of conventional welds and bi-material (dissimilar) joints. Figure 3 presents the weld metal and HAZ notched SENB and wide-plate specimens for various measurement quantities including local strain measurements (by strain gauges) to be made on the wide-plates. These local strain values (RS and LS) and gauge length strain (GLS) are of interest to determine the strain values at the respective parts of the mis-matched welds. For both specimens the CTOD measurments can be made by using the local CTOD(δ_5) measurements.

The crack mouth opening displacement (CMOD) measurement (of standard fracture toughness testing procedure on SENB and CT specimens) as conducted on a part of the crack face must bear some relation to crack tip displacements even in the strength mis-matched cases, but the nearer displacement measurements are made to the crack tip itself, the more reliable they are likely to be [42, 43]. Applying δ_5 measurements developed at the GKSS on a 5 mm gauge length perpendicular to the crack at its tip is a useful method of conducting measurements to indicate crack tip opening behaviour in fracture toughness tests [43]. This way of locally measuring CTOD(δ_5) for weld metal, HAZ and bi-material interface toughness testing can be considered as the most meaningful method, since it provides local measurement without the need to infer from remotely measured quantities, like standardised J-integral and CTOD. This is of particular importance when the specimen is mechanically inhomogeneous, as is the case for mis-matched welds and bi-material interfaces since an interface crack and HAZ of mis-matched joint exhibits a CTOD composed of the contributions from either side of the crack. At present, there is no available specific standard for the fracture toughness testing of heterogeneous materials (weldments). Therefore, the conditions under which standard test methods for homogenous materials can be applied should still be clearly defined. They are given by parameters such as mis-match ratio, M, 2H/(W-a), 2H/B, notch location and others (2H is the width of the weld metal).

Weld metal notched SENB specimens

It is generally believed that the mismatch effect on fracture toughness can be ignored if the width of the weld metal (2H) is greater than the uncracked ligament (W-a). Such geometrical condition (a/W=0.5, 2H/(W-a)>1) of the three point bend specimen (SENB) ensures that plasticity developing in the weld metal would be similar to that of an homogenous all-weld metal specimen for up to certain level of mis-matching (about up to 50%). With decreasing weld metal width increasing interaction of the weld metal plasticity with the surrounding base plate occurs and hence the effect of weld metal mismatch on standard CTOD or J must be expected. In other words, for shallow cracked SENB specimens (corresponding to a/W=0.1 and smaller 2H/(W-a) ratio), the global deformation of the overmatched specimen will be very similar to that of the softer base metal. The plastic zone spreads out of the weld region into the softer base metal. For such cases, the standard fracture toughness testing procedures will not provide correct estimates of the fracture toughness. It is recommended that local measurement of displacement should be used for evaluation of the toughness value [46]. Despite recent studies, one may still describe the current situation as;

> Elastic-plastic fracture characterising parameters, such as standardised CTOD and J, are not available for mis-matched welds in a straight-forward manner. Most of the studies conducted deal with the effect of mis-match on J and

CTOD using specimens notched at the weld center line. The HAZ studies have been performed are limited.

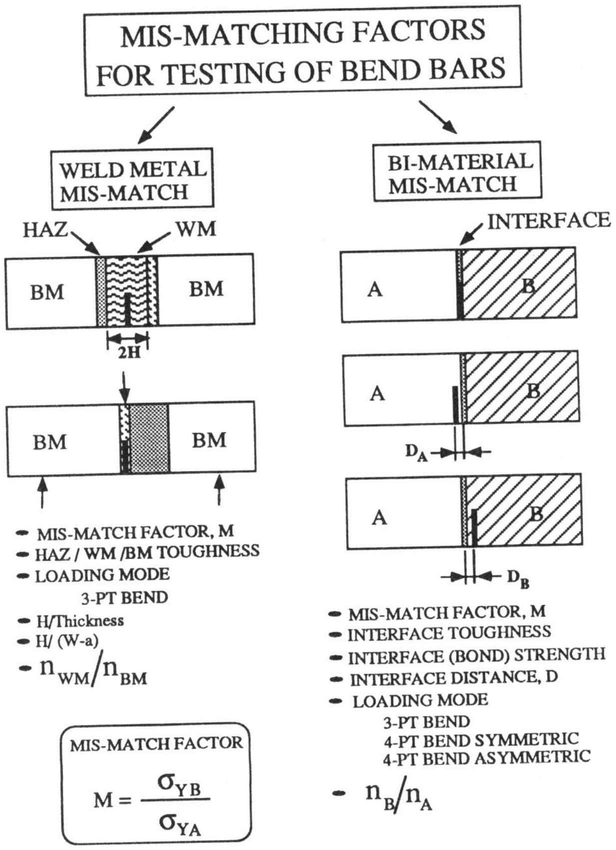


Figure 2 Some factors to be considered in fracture toughness testing of mis-matched or bi-material bend specimens

Heterogeneous structural welds can also be obtained when plates from various sources, supplier are welded together. This heterogeneity affects the level of weld metal matching and consequently the required fracture toughness for adequate weld performance. In addition, when the base plate yield strength variability is significant, problems may arise in welding procedure qualification since compatible welding consumables are selected on the basis of the base plate minimum specified yield strength (SMYS). Such heterogeneous structural welds require re-consideration of the welding qualification fracture toughness test requirements with respect to yield strength variation. Toughness testing should be conducted on plates from the lower end of the yield strength distribution. In particular, testing should be concentrated on the HAZ of the lower strength base metal because any plastic straining will be concentrated there.

HAZ notched SENB specimens

For defects in the HAZ region of welds the actual measured fracture toughness value may be reduced by overmatching weld metal, and it is important that toughness measurements are made on joints fully representative of mis-matched strengths. In general it should be assumed that yielding at cracks in the HAZ of mis-matched welds will be controlled by the material with the lower yield strength.

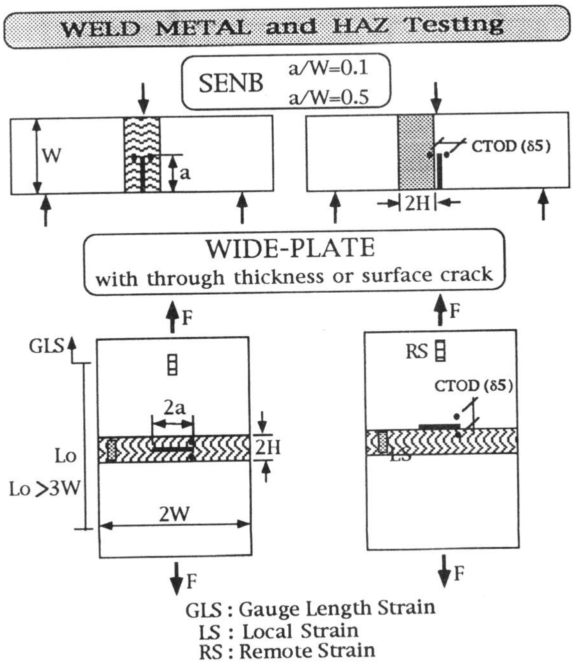


Figure 3. Shematic illustrating two basic specimen configurations for testing of welds including some of the quantities to be used in the fracture analysis.

Minami and Toyoda et al [25] have recently reported the results of the FE work on the effect of strength mis-match on HAZ notched CTOD steel welds. For the embrittled HAZ, the overmatch condition lowered the critical CTOD value of the HAZ due to the elevation of the local stress in the HAZ (independent of the specimen geometry) caused by the constraint effect of the overmatched weld metal.

Generally, a softer environment should relax the conditions for brittle fracture; an effect of this kind has been observed by Koçak et al [3] in the test series conducted to examine the critical CTOD values of the coarse grained heat affected zone of StE460 steel where an undermatching (M=0.54) weld metal (which in fact represents a configuration giving rise to overmatching of the CGHAZ with respect to the adjacent weld metal) resulted in a dramatic increase of the critical CTOD as compared to overmatching (M=1.16 and 1.71) weld metals as shown in Figure 4. Furthermore, for highly overmatched welds the loss of crack tip constraint on shallow cracked overmatched SENB specimens was almost fully compensated by the mis-match (overmatch) induced constraint and hence low toughness values similar to the deep notched specimens were obtained.

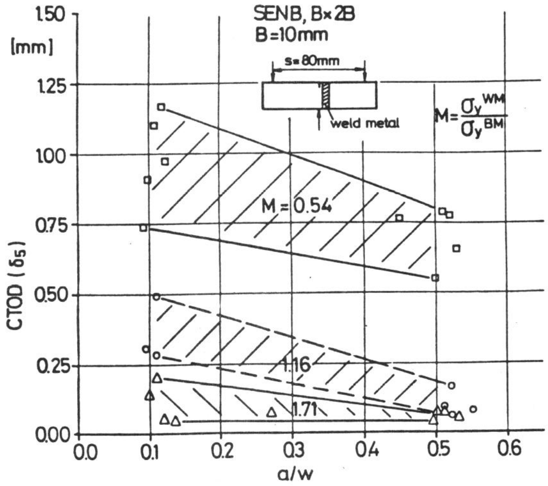


Figure 4. Locally measured CTOD vs. crack depth of the mis-matched SENB specimens showing the effects of M and a/W on the HAZ toughness [20].

Determination of J-integral for mis-matched welds

Attempts have been made by Joch and Ainsworth et al. [45, 46] to accomodate the effect of strength mis-match in the η-factor with some modifications for strength mis-match to calculate J from the area under load-load line displacement curve in case of deep notches. According to this study on strength mis-matched SENB specimens, the η-factor is a function of the mis-match ratio, M and H/(W-a_0) ratio. Futhermore, Kirk et al. [12, 15, 16, 36, 47] and Gordon et al [48] have proposed a new J-estimation scheme using the area under the load-CMOD curve (J_{CMOD}) for homogeneous and mis-matched specimens for a large range of crack size (a/W from 0.1 to 0.5) as given by eqn. (1).

$$J = \frac{K_I^2}{E'} + \frac{\eta_C A}{B(W - a_0)} \qquad (1)$$

where A is the plastic part of the area under the load-CMOD curve, B is the specimen thickness, W the specimen width and a_0 the initial crack length,

For homogeneous specimens :

$$\eta_C = 3.5 - 1.4167(a_0/W) \tag{2}$$

For strength mis-matched specimens:

$$\eta_C = \left[3.5 - 1.4167(a_0/W)\right]\left[\frac{\sigma_{YB}}{\sigma_{YW}} + \left(\frac{1-\sigma_{YB}/\sigma_{YW}}{2}\right)\right] \tag{3}$$

Recently, a study [44] on the effect of strength mis-matching on the CTOD (δ_5) and J R-curves was carried out at the GKSS research center using both modifications of the η-factor to estimate the J-integral for homogeneous and highly mis-matched SENB specimens, Figure 7. The CTOD(δ_5) and J R-curves are shown in Figures 8 and 9 respectively. The CTOD(δ_5) R-curves were obtained from CTOD measurements using the δ_5 clip gauge at the original fatigue crack tip, Figure 8. The J-values were estimated from the area under the load-CMOD curves as proposed by Kirk et al. for homogeneous and mis-matched SENB specimens using the respective η-factor. A comparison of the R-curves obtained from homogeneous all-weld metal and mis-matched (undermatched, UM and overmatched, OM) specimens identifies the effect of strength mis-matching on the R-curves depending on the fracture toughness parameter used.

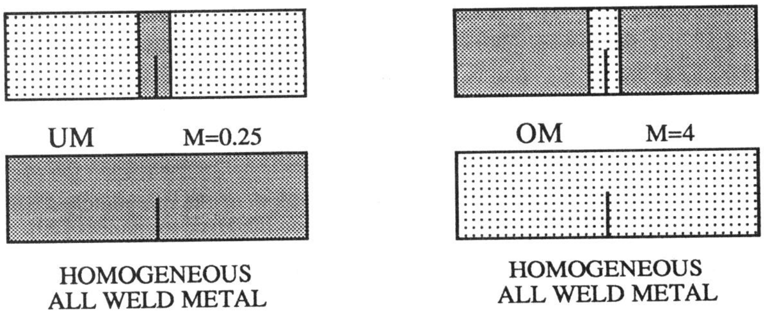
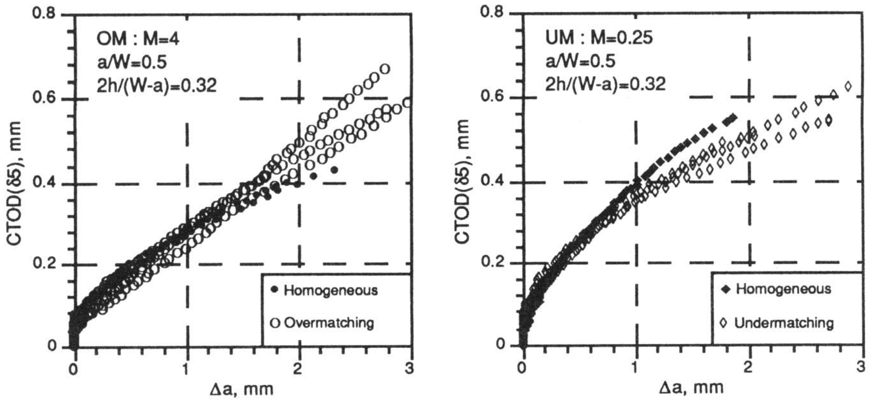


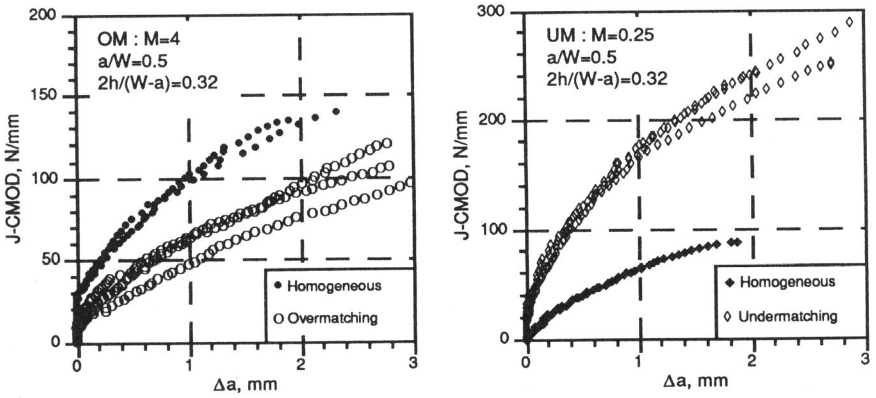
Figure 7 The SENB specimens (a/W=0.5) used to determine the weld strength mis-match effect on the R-curves. A comparison is made between UM or OM specimens (middle strip which simulates the weld metal is electron beam welded) with their respective all weld metal specimens.

The comparison between the mis-matched and the homogeneous specimen results in Figure 8 clearly shows that even extremely high over- and undermatching have no measurable influence on the CTOD(δ_5) R-curves due to the local nature of the δ_5-clip measurements which do not include any remote deformation to the crack tip plasticity. Figure 9 presents the J R-curves for mis-matched and homogeneous specimens deep notches, where J is calculated from the area under load-CMOD curves with η_C factor given by eqn. (2) for homogeneous specimens and eqn. (3) for mis-matched configurations.



a) b)

Figure 8 The CTOD (δ_5) resistance curves of the SENB specimens shown in Figure 7 showing unique R-curves independent of mis-matching; a) comparison between OM and homogeneous specimens, b) comparison between UM and homogeneous specimens [44].



a) b)

Figure 9. The J R-curves of the deep notched SENB specimens shown in Figure 7, showing different R-curves for homogeneous and highly mis-matched specimens; a) comparison between OM and homogeneous specimens, b) comparison between UM and homogeneous specimens. (Note: J-CMOD is calculated by eq. (1) with η_C given by eq (2) for homogeneous specimens and η_C given by eq. (3) for mis-matched specimens) [44].

A very large difference between the R-curves obtained for undermatched and homogenous all-weld metal specimens can be seen in Fig. 9b, although for both specimens the material where the crack tip is located is identical. For the overmatched case, however, the reverse situation was obtained by getting the lower R-curves for overmatched specimens compared to the homogenous all-weld metal specimen R-curves, Fig. 9a. Clearly, the use of the J estimation procedure using the area under load-CMOD curve and an adjusted η_C factor for mis-matched specimens did not produce unique R-curves for a given material where the crack is positioned. This discrepancy is due to the limit on the range of applicability of this J estimation scheme with respect to the degree of mis-matching and also possibly due to the weld width (2H) effect which eqn. 3 does not take into account. A numerical study conducted by Franco and Gilles et al [49] showed that for deeply cracked SENB specimens (i.e., H/(W-a)>0.5) and for mis-match factor, M, ranging from 1 to 3, the standard ASTM E 813-88 procedure (using area under load vs. load line displacement curve and considering mechanical properties of the weld metal) provided good estimates of the crack driving force J.

The accuracy of J-estimation procedures for mis-matched SENB specimens has also been studied by Eripret et al [27, 40] by comparing the calculated J-contour integral value and the energy J-value derived from the load-load line displacement curve using the standard ASTM E813-88 procedure. This work concludes that experimental determination of J-values needs great care since such J-values include some amount of plastic strain energy dissipated in the softer base metal (for overmatching case), which does not play any role in crack initiation. This energy quantity (J-value) is considered by Eripret et al as an "apparent toughness" of the structure, that is measured experimentally but does not represent the real loading which the crack tip is subjected to. However, they report that the ASTM E813-88 procedure provides reasonable estimates of the crack driving force J for deep notched SENB specimens (H/(W-a)>0.5) and M= 0.8 to 1.5.

Gordon and Wang [48] have reported the FE results of the project to assess the effects of mis-match on fracture toughness testing and analysis procedures (both ASTM and BSI). Their results indicate that the standard ASTM J and CTOD estimation procedures provide reasonably accurate estimates (within 10%) of J and CTOD for deeply notched (a/W=0.5) welded SENB specimens notched into weld metal for mis-match levels ranging from up to M= 0.75 to M= 1.25. Their numerical analysis further revealed that J and CTOD may produce different trends when applied to characterize the toughness of narrow gap welded joints, since as the weld width is decreased, the m factor which relates J and CTOD exibited a strong dependence on mis-match level. It is apparent that there exist considerably different opinons on the range of applicability of the existing CTOD and J fracture toughness procedures for weld metal testing with deep notched SENB specimen. Undoubtedly, the effect of weld metal mis-match on the standardised CTOD and J testing is a function of degree of mis-match, weld width and crack size. This effect becomes more pronounced as the degree of mis-match increases and crack size (a/W)and 2H/(W-a) ratio gets smaller.

WIDE-PLATE TESTING

Figure 3 schematically shows the wide-plate testing of weld metal and HAZ regions of transverse butt welds. Generally, the wide-plate testing requires simple instrumentations which includes measurements of CMOD, GLS, CTOD and if required local strain levels with an adequately positioned strain gagues. Figure 8 present typical CMOD vs. applied strain (GLS) curves depending on the defect size and mis-match level. In general, wide-plates with relatively large defects tend to produce net section yielding (NSY) whereas small defects and adequate strain hardening capacity are beneficial for obtaining the gross section yielding (GSY) mode of deformation, Figure 8b. It is safe to use the base metal plastic straining requirement as a simple engineering criterium for the weld joint performance[50].

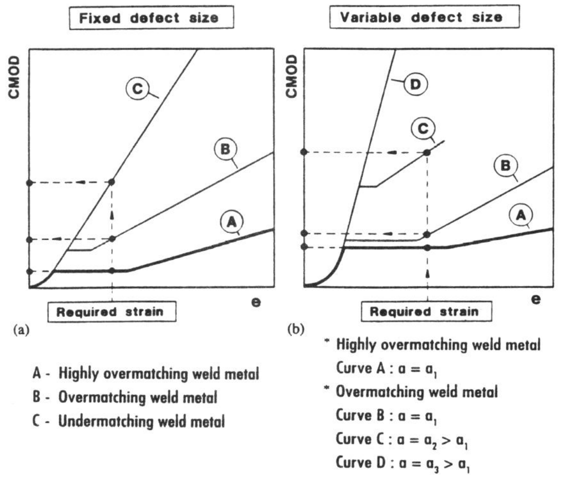


Figure 8 Schematic illustrating the dependence of the CMOD on applied strain as a function of a) the degree of weld metal overmatching for a fixed defect size and b) defect size for a fixed level of overmatching (curves B, C and D) [50].

Effect of mis-matching on the HAZ fracture behaviour

A series of FE analyses have been conducted by Toyoda and Minami et al [51] on the HAZ notched wide-plates containing transverse mis-matched welds loaded in tension. The stress-strain field development at the crack tip showed, as expected, that the plastic strain accumulated preferably in the HAZ side for the overmatched joint, and in the weld metal side for the undermatched joint. According to this investigation, overmatching resulted in a reduction of fracture initiation resistance of the HAZ. This study has therefore concluded that evenmatching is the most desirable condition for optimum weld joint performance since the use of undermatching decreases the fracture resistance of the weld metal due to the increase of constraint. The effect of mis-match on the constraint conditions at the crack tip should therefore be considered. For a long uncracked ligament, (W-a), the normal stresses can be substantially higher than for an all weld metal case. This is due to the restraint provided by the environment to the undermatched strip; thus, the crack driving force as given by CTOD or J is decreased as compared to all weld metal plate, whereas the constraint increases. The reverse is expected for overmatching. The conclusion to be drawn for fracture behaviour is that materials or phases which are subject to normal stress controlled fracture such as cleavage, should not be emdedded in an environment of higher strength.

Harrison and Webster [32] have concluded their study on the effect of weld metal strength and HAZ toughness on wide plate performance by saying that "for the best wide plate performance a combination of high weld metal strength (overmatching) and high CTOD is required. Poor wide plate performance could be expected with low HAZ CTOD irrespective of weld metal strength".

Longaygue et al [26] have conducted a numerical investigation on the HAZ notched wide plate configuration by varying the HAZ and weld widths as well as their yield strengths in order to determine the size and mis-match effects on the performance of the specimen. According to their study, overmatching is not necessarily the best possible way to improve the performance of welded structures with respect to the risk of brittle failures of HAZ. Even 20% overmatching can lead to reduced performance of the weld assembly if its fracture resistance is controlled by the HAZ toughness properties. Finally, they recommend evenmatching as a best solution and hence attention should be paid to minimize the amount of mismatching.

The plastic strain distribution in and near the mis-matched V- and X-groove welds has been investigated by Denys et al [50]. This work revealed that for undermatching V-groove welds, the highest strains occured in the weld metal and HAZ regions (highest at the root side and adjacent HAZ). For overmatching welds the opposite effect has been observed. The HAZ strains in the root region were smaller than those at the cap side. It should be noted that the HAZ strains in the overmatching weld were found to be smaller than the base metal strains (strain deconcentration effect). The observations made on the experiments conducted by Denys suggest that an overmatching V-groove weld metal provides considerable protection of the weld metal root (including its HAZ) against imposed plastic strain.

An investigation conducted by Petrovski and Koçak [34] on surface cracked tensile panels with X-groove mismatched weldments revealed a significant shielding effect of overmatching (only 6%) on the weld metal and HAZ cracks by reducing the crack driving force J (compared to the base plate) as shown in Figure 9. This plot further demonstrates that weld metal undermatching (26%) is detrimental for both weld metal and HAZ cracks.

As can be seen from these examples of the open literature opinons are conflicting on the effect of overmatching on HAZ cracks. This issue clearly calls for further investigation and indicates that present knowledge is not ready to make practical recommendations for establishing the role of overmatching on HAZ crack. It should be noted that numerical modelling of the HAZ crack is generally conducted by using strips of material (weld metal or HAZ) with idealized material properties and weld geometries with through thickness cracks. Interaction between geometrical factors and property gradient existing at the vicinity of the crack of a real weld joint need to be considered since they significantly affect the plasticity development.

DEFECT ASSESSMENT PROCEDURES

In structural weldments the tensile characteristics of the weld deposit differ from those of the base metal. Conventional design rules and defect assessment procedures do not directly address the strength mismatch effect on the weld joint performance. It is known that the plastic yielding pattern in and around the weld metal has a significant effect on the tolerable defect size. Because of the close connection between the yielding pattern and weldment performance, the level of strength mismatching is a most important factor if a designed stress concentration, a defect, or a possible overload causes plastic deformation.

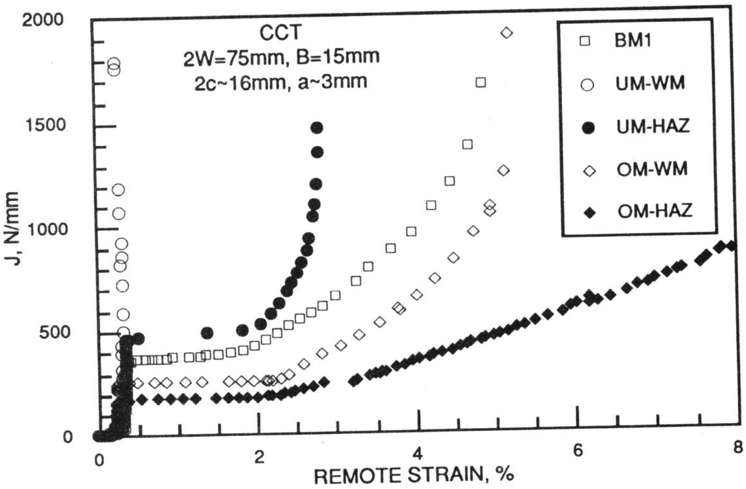


Figure 9. Effect of mis-matching on the crack driving force J for undermatched (UM) and overmatched (OM) surface cracked welded plate loaded in tension [34].

Welded engineering structures are normally designed to perform within the elastic stress range of the base metal. Of course, the use of a design stress which is some fraction of the yield strength does not automatically mean that nowhere in the structure the design stress exceeds this fraction. The yield strength mis-match does not affect deformation behaviour in the elastic loading range, i.e., as long as the applied stress is smaller than the lowest yield (base or weld metal) strength. However, as soon as yielding occurs in the weld or base metal, yield strength mismatch is to be considered for transversely loaded weldments. It is rational to require from any defective weldment to sustain remotely applied stresses of base metal yield strength magnitude. The need for adequate plastic straining capacity of the wide plates can limit the use of undermatching weld metals. The problem is that the performance characteristics are dominated by the load-deformation behaviour and the toughness characteristics of the "soft" weld metal. Thus, defective undermatching weld metals exposed to plastic straining require adequate strain hardening and high toughness to prevent failure at low overall strain levels. On the other hand, overmatching weldments permit more straining than undermatching ones, Figure 8a. From this viewpoint, it is attractive to ensure weld metal yield strength overmatching because it is then possible to allow relaxation in the weld metal toughness requirements.

It is rational to require a defective weldment to sustain remotely applied (gross) stresses of the base metal yield strength magnitude. Obviously, the requirement of base metal yielding for safe structural performance implies that the overmatching (yield strength of weld metal is higher than the base metal) case is desirable because yielding of the base metal (GSY) can be more easily obtained even for comparatively longer defects and furthermore, it implies that strain at failure will be plastic. However, the yield strength, weld height (2H) and strain hardening capacity of the weld metal region as well as defect position/shape/size will affect the yielding behaviour of the weldments. In particular, the interdependence of these variables should be established in order to determine the toughness needed for mismatched weld materials for safe and economic considerations.

A number of defect assessment methods have been developed which are supposed to cover the assessment of the severity of crack-like defects in welded joints. However, these methods are based on homogeneous materials and generally assume that defects present are located in material of uniform mechanical/microstructural properties and it is normal practice to use the tensile properties of the material in which the defect is located. However, in reality, the mechanical heterogenity will influence the plastic zone development process at defects and hence affect the relationship between crack driving force and applied loading. A defect assessment procedure on the basis of the CTOD design curve, for example, requires an effective applied strain parameter. Yet, the determination of this parameter in defective mismatched welds presents a considerable difficulty since the development of the strain level in the weld metal depends on the relative difference between yield strengths of the weld and base metals. A proper definition and measurement technique of the overall applied strain (and its relationship with local strain) for the transversely loaded mismatched welds are still required. For mismatched welds, the relationships defined between crack driving force and applied strain differ from those of an homogeneous plate material.

It would be most desirable to have a defect assessment procedure which provides separate (for UM and OM welds) and accurate predictions (mainly by taking account of the effect of mis-match on the yield load) for defective mismatched welded structural components.

CTOD design curve (PD6493) procedure and mis-match effect

The mechanical heterogeneity of a material or welded structure has to be taken into account if the driving force of a crack is to be determined. First of all, for undermatched and overmatched conditions, limit load solutions differ from those of a single material. However, as far as quantitative defect assessment is concerned, the BS PD6493: 1991, CTOD Design Curve procedure gives guidance on methods for assessing the acceptability of defects in fusion welded engineering structures and does not consider mis-match effects. There is no provision for the possible interaction between base plate and weld metal and hence on the crack tip deformation behaviour of welded structure. Nonetheless, some researchers use them to assess the behaviour of cracked mis-matched joints; in these cases the specimens are modelled as all weld metal or all base plate configurations and the applied strain (usually gauge length strain used) is normalized either with the yield strain (e_y) of base or weld metal. Figure 10 shows schematically the effect of mis-matching and weld width on the crack driving force in comparison with the CTOD Design Curve (all plate).

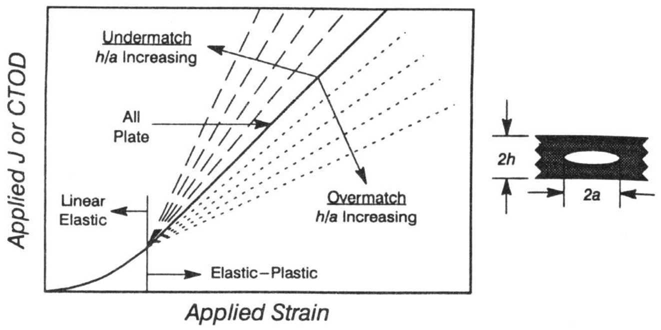


Figure 10. Effect of weld strength mis-match on driving force relations expressed in design curve format for a fixed a/W [36]

Harrison and Webster [31] have recently examined the results of about 50 HAZ notched wide-plate tests to determine the effect of weld metal strength on "wide-plate CTOD" and the findings have been used to assess the implications for defect assessment procedure (PD6493:1991). The lower levels of weld metal strength resulted in higher wide-plate CTOD values (applied) for a given level of plastic strain. Their work concluded that PD6493:1991 level 1 is unable to predict the mis-match effect and would give unsafe predictions of behaviour in wide-plate tests having very low levels of weld metal strength overmatch. The results of the investigation carried out by Hornet and Koçak et al [52] have also demonstrated the inability of this procedure to provide accurate predictions. The results of the CCT panels with a through thickness weld metal (20% under- and overmatched) crack have been compared with the CTOD Design Curve estimation as shown in Figure 11. The applied strain, e_R has been measured by the strain gauge at the remote base metal part and normalized with the yield strain of the base metal, e_{YB}. However, as mentioned above the PD 6493 procedure requires to use the mechanical properties of the material in which the crack lies.

The CTOD Design Curve shown in this plot largely underestimates the crack driving force for undermatched panels since it can only provide a single curve for both cases. The crack driving force is highly underpredicted by the CTOD design curve at strain level beyond the linear elatic regime (i.e $e_R/e_{YB}>0.5$). Similarly, a systematic underestimation of the crack driving force for undermatched specimens has also been reported by Kirk and Dodds [36] and they concluded that the CTOD (and J) design curves should not be applied to undermatched welds. In their analysis, for overmatched welds, the CTOD design curve overestimated the applied CTOD for more configurations than the J-design curve overestimates the applied J. According to the limited available information in the open literature the use of CTOD and J-design curve procedures to predict driving force to fracture for welded structures generally produces a systematic trend as follows;

- significant underestimation of the crack driving force for undermatched welds and hence, neither design curve works well,
- for overmatched welds, highly conservative estimate of the crack driving force has often been observed particularly for high overmatch levels.

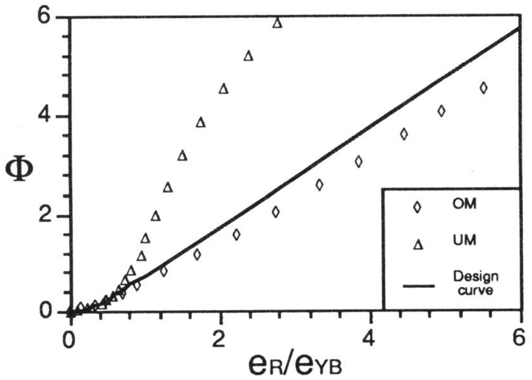


Figure 11 The CTOD Design Curves for 20% mis-matched austenitic steel CCT panels (a/W=0.15). Applied strain e_R normalized with the base metal yield strain [20].

ETM-MM procedure
The effects of the strength mis-match of a welded joint on fracture toughness and crack driving force have been studied systematically at the GKSS. Some of the results of this work are given in references [14, 19, 30, 35, 52-57]. In these studies, the Engineering Treatment Model for mis-matched welds (ETM-MM) has been used for estimating CTOD (measured in terms of δ_5) or J as crack driving force parameters. A first attempt account for mis-match effects is provided by this model. It estimates the CTOD(δ_5) as a function of applied strain or applied load.

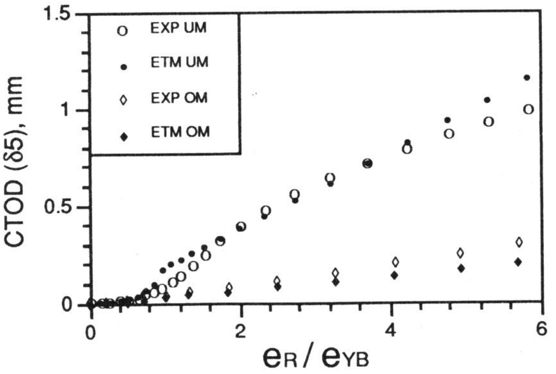


Figure 12. Comparison between the ETM-MM estimations (ETM UM and ETM OM) and experimental results (EXP UM and EXP OM) of the austenitic CCT panels, see Fig. 11 for comparison with the CTOD design curve estimation [20]

The formalism of this model has presently been derived for a through thickness crack at the middle of the weld metal of a transverse loaded butt welded wide plate. In such conventional wide plate configurations the crack is in the centre line of the strength mis-matched weld metal - which can be idealised as a narrow strip of material (weld metal) embedded in an environment (base metal) with a different stress-strain curve. Figure 12 presents the comparison between the ETM-MM estimation and experimental results (used also for CTOD Design curve, see Fig. 11) of 20% under- and over-matched austenitic steel CCT panels (a/W=0.15). In this plot, the remote base plate strain, e_R as measured by strain gauge, was used as an applied strain and normalized again by the base metal yield strain. It can clearly be seen that the ETM-MM provides two separate very good crack driving force estimations by distinct benefit of the OM configuration for a given applied strain compared to the UM which gives a much higher crack driving force, as expected. This model not only includes the mechanical properties of the base and the weld metal (σ_{YB}, σ_{YW}, n_B, n_W) but also the geometrical parameters (a/W, H/(W-a) and H/B) of the welded specimen or component, since the geometry (width of the weld, 2H and size of the uncracked ligament, W-a) of the defective mis-matched weld joint significantly influences the deformation and fracture behaviour of the specimens.

Limit load considerations for mis-matched configurations

The yield load of the center craked homogeneous wide-plate in tension is determined (plane stress) as:

$$F_Y = 2B\sigma_Y(W - a) \qquad (4)$$

For overmatching welds the yield load, F_{YOM} and strain hardening exponent of the whole mismatched system n_M depend on the mode of the plastic zone development at the uncracked ligament (W-a) of the wide-plate specimen. The entire deformation mechanism of the over- or under-matched specimens and hence the description of the yield loads differ significantly from those for homogeneous base metal specimen analysis. The degree of influence of strength mis-match on the limit load depends on the mis-match level (M), weld height (2H) and crack size (a/W, H/(W-a)). For overmatched specimens, the plastic deformation mechanism is expected to cross the weld/base metal interface (mis-match boundary), then penetrating into the base metal. For both plastic zone development of the wide-plates with through thickness crack at the center of the weld metal, the following definition of the limit load, F_{YM}, and strain hardening exponent for mis-matched configuration, n_M developed by Hao et al [30, 35, 54, 58, 59] at the GKSS as a function of the mis-match factor (M) and weld geometry can be used:

For **plane stress** :

if plastic zone remains within the weld metal (UM condition);

$$F_{YM} = 2B\sigma_{YB}\left[(W - a - 1.89H)\frac{2}{\sqrt{3}} + 1.89H\right] \qquad \text{for } (W - a) \geq 1.89 \qquad (5)$$

if plasticity penetrates into the base plate (OM condition);

$$F_{YM} = 2B\left[1.54H\sigma_{YW} + (W - a - 1.54H)\sigma_{YB}\right] \qquad \text{for } \frac{(W - a)}{H} \geq 0.7 \qquad (6)$$

the mis-match hardening exponent, n_M may be estimated by
for OM condition

$$n_M = \left[1.54Hn_W + (W - a - 1.54H)n_B\right]/(W - a) \quad (7)$$

For plane strain condition and further details of the slip-line considerations for yield load determination are given in refs. 58 and 59. For undermatching condition n_M should be set equal to n_W if n_W is smaller than the n_M value determined by the equation. Zhang et al [4] has used the term of equivalent strain hardening exponent, n_e, and found that for H/(W-a) larger than 1.0, the n_e value is very close to the exponent of the weld metal for all mis-matching conditions.

These expressions provide closed form formulations for limit load and strain hardening factors for mismatched CCT configurations respectively. Both expressions contain the effects of strength differences between base and weld metals as well as the geometrical dimensions of the cracked weld zone. Obviously, the use of both expressions in the structural analysis of mismatched welds should significantly increase the accuracy of the predictions.

CONCLUDING REMARKS

- Generally, the yield strength of the weld metals is determined using "all-weld metal" round tensile specimens. The degree of mis-matching should be determined using such specimen results but also taking into account the yield strength variabilty within the weld deposit.

- The ratios of the weld metal width to uncracked ligament, 2H/(W-a) and weld metal width to plate thickness, 2H/B play an important role in the plasticity development around the weld joint and hence in the welded plate.

- In general, many center cracked (weld metal notched) wide-plate test results (experimental or numerical) have shown the **beneficial effects of weld metal strength overmatching** by promoting failure in the lower strength but higher toughness base plates. However, increasing defect size decreases the beneficial effect of overmatching.

- In undermatched welds, applied strain is concentrated in the weld metal and hence such weldments require adequate strain hardening and high toughness to prevent failure at low overall strain levels. The need for adequate plastic straining capacity can limit the use of undermatching weld metals.

- There are conflicting opinions about the beneficial effect of the overmatching weld metal **for HAZ cracks in wide-plate testing**. The view that there is a shielding effect of the overmatched weld deposit on generally lower toughness HAZ has not fully been shared by all researchers. However, for SENB specimens, it has been shown that the HAZ CTOD toughness decreases with increasing adjacent weld metal yield strength. Mode of loading is an important factor for determination of the mis-match effect in general.

- There exist considerably different opinons on the range of applicability of the existing CTOD and J fracture toughness testing procedures for mis-matched weld metal testing with deep notched SENB specimens. So far there is too little information to formulate any unified practical recommendations for testing of weld and HAZ using standard procedures.

- For testing of highly mis-matched weldments using standard SENB specimens, the simple and direct CTOD(δ_5) technique provides a straightforward means of determining toughness of R-curves, independent of the mis-match level.
- It would be most desirable to have a defect assessment procedure which provides separate and accurate predictions (by taking account of mis-match effect on the limit load) for defective under- and overmatched welded structural components.
- The CTOD- and J-Design Curve procedures do not consider mismatch effect and should not be applied to undermatched welds. For overmatched welds, both design curve procedures highly overestimate the applied CTOD and J.
- A complete defect assessment procedure for wide plates containing strength mis-matched welds is available in a procedural form including modified limit load and strain hardening exponent for mis-matched configurations in the formalisms of the ETM-MM. It should be noted that presently no other defect assessment procedure has yet put forward any model to include the strength mis-match effect on the defect assessment procedure to avoid any under estimation of the crack driving force or critical defect size.
- The trend to higher strength steels poses the problem of achieving overmatching weld metal and retaining acceptable weld metal toughness. A need exists to examine the degree of possible relaxation in the weld metal toughness requirements by considering the shielding effect of overmatching weld metal.

Acknowledgements - The authors would like to thank Prof. K.-H. Schwalbe for his valuable comments on the manuscript.

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