WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL*, FEBRUARY 1989

Sponsored by the American Welding Society and the Welding Research Council

RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT

Difference between Small- and Large-Scale Testing of Weldments

An evaluation was made of the weld metal overmatching effects in relation to weld joint performance

BY R. M. DENYS

ABSTRACT. It is often experienced that low weld metal toughness properties as conventionally measured with small-scale test specimens do not always reflect poor weld joint performance. Particularly, when weld metal yield strength overmatches that of base metal, considerable differences in small-scale (crack tip opening displacement – CTOD) test and large-scale (wide-plate) test performance are observed.

The objective of this paper is to examine the difference in behavior between small- and large-scale weld metal tests. For this purpose, the crack driving force for fracture in a tension-loaded weldment is related to the applied strain and equated to the fracture-resistance properties of the weld metal.

It is concluded that both information on the apportionment of the applied deformation in a weldment and the degree of weld metal overmatching are key factors when weld metal toughness requirements are to be specified. Furthermore, the results of the theoretical analysis and the experimental data illustrate that occasional low weld metal toughness properties are not a reason for concern provided the weld metal yield strength overmatches that of the base metal. Finally, the practical implication is that if weld metals overmatch the base metals in yield strength, a relaxation in toughness requirements for the weld metal compared to the base metal is allowable.

R. M. DENYS is a Lecturer at Rijksuniversiteit, Gent, Belgium.

Introduction

In order to avoid weld metal fracture in steel structures, it is commonly required that the weld metal tensile strength matches, or slightly exceeds, that of the base metal. For an important number of welded steel structures including storage tanks, pressure vessels, pipelines, offshore platforms, bridges and so forth, there also exists the additional requirement of low-temperature notch or fracture toughness, which necessitates the use of alloyed weld metals.

KEY WORDS

Weldment Testing
Small-Scale Testing
Large-Scale Testing
Testing Differences
Fracture Toughness
Crack Opening
Crack Tip Opening
Weld Overmatching
Wide-Plate Testing
CTOD Testing

Since the alloy additions in the weld metal also increase its strength, it is well known that the weld metal strength may appreciably exceed (overmatch) the base metal strength, and the weld metal yield strength will then also overmatch the base metal yield strength. When such weld metals are used for joining structural steels having yield strengths up to about 450 N/mm^2 (65.3 ksi), the weld metal yield strength can be 20 to 40% higher than that of the base metal. Likewise, because of the dilution effects, the HAZ region might also be overmatched in the case of conventional steels.

If the weld metal yield strength is higher than that of the base metal, it will proportionally deform less in a transversely loaded weldment than the "softer" base metal. This means that, provided certain conditions with regard to the size of the discontinuity are satisfied, overmatching weld metal can protect weld metal discontinuities from severe plastic straining. From this point of view, it seems attractive to assure a significant degree of weld metal overmatching. Unfortunately, there is at present little experimental data available to quantify this assumption in depth. On the other hand, the experimental information needed is not easy to produce, largely because small fracture tests are not suitable for the purpose.

The ongoing discussion on weld metal toughness requirements and the fact that these requirements are not firmly established encouraged the author to study the interaction between the crack driving force for fracture and the degree of weld metal overmatching. Indeed, by analyzing the deformation behavior of a tension-loaded weldment, an analytical relationship can be established between the crack driving force for fracture, as measured in terms of applied crack opening displacement (COD) and as a function of the applied strain. As a result, the degree of weld metal overmatching will be developed and validated by examining some typical experimental data.

Weld Metal Notch Toughness Requirements

The effect of the differing mechanical properties of the various zones, *i.e.*, weld metal, heat-affected zone and base metal, in a weldment is usually assessed with the transverse-weld (cross) tensile test. When the weld metal tensile strength overmatches that of the base metal, fracture will take place in the base metal and the apparent ductility of the weldment will be high.

It is also well known that these zones have widely differing toughness properties, however, and we should not ignore this. It is only when a cracked specimen is tested that fracture may occur with much reduced ductility and that an indication of brittle behavior may be obtained. The reason for the difference between cracked and uncracked specimen deformation behavior is associated firstly, with the concentration of stresses at the tip of a crack-like discontinuity, and secondly, with the fracture-toughness properties of the weld metal. As a consequence, the main concern about the performance characteristics of a defective weld metal (or heat-affected zone, HAZ) is related to its notch/fracture toughness. In this context, it is thus essential to ensure adequate weld metal, HAZ or base-metal toughness. However, the deformation and eventual fracture behavior of the weld metal in relation to the deformation behavior of both the HAZ and the base metal is a problem area that is not yet well researched.

The weld metal toughness and weld joint property assessment tests for fracture resistance are mainly evaluated by means of small scale tests (Refs. 1-5). At present, codes and specifications stipulate small scale Charpy V-notch impact and/or fracture mechanics CTOD test requirements, which are apparently based on the principle that the toughness required for the base metal should also be obtained for the weld metal. The toughness requirements derived from those kind of tests are debatable for transversely loaded weld metals that overmatch the base metal in yield strength, because the weld metal does not have to perform and, provided certain conditions are satisfied, the plastic strains in a cracked weld metal are normally very small. Hence, it might be expected that the required weld metal toughness levels for adequate weldment performance may be lower than those specified for the base metal. Because of the complexity of the deformation behavior of a weldment, the results of small-scale tests do not always conform to the performance of a weldment. This implies that, whatever small-scale tests are used for measuring the weld metal toughness, it is important to recognize that those tests require more large-scale test data for establishing realistic correlations between weld metal toughness requirements and adequate weld joint performance.

CTOD Fracture Toughness and Weld Metal Matching

Because of the practical importance of CTOD performance requirements, it is intended in what follows to give a brief perspective view of the weld metal CTOD property requirements in relation to the matching effects in transversely loaded weldments. The implications of the relative differences between the weld metal (σ_{Ywm}) and base material (σ_{Ypl}) yield properties on CTOD toughness can be evaluated by interpreting them in the same terms as the design curve does. The effect of weld metal matching can then be taken into account by using σ_{Ywm} and σ_{Ypl}, respectively for substitution into the design curve (Refs. 6, 7).

Given the same allowable crack size and for a design stress equal to a fraction, a, of the base metal yield strength: $\sigma = a \cdot \sigma_{Ypl}$, with $a > 0.5$, the weld metal CTOD ($CTOD_{wm}$) can be related to the base metal CTOD ($CTOD_{pl}$) by using the design curve equation:

$$CTOD_{wm} = CTOD_{pl} \cdot \frac{a + x \cdot b - 0.25 \cdot b}{a - 0.25} \qquad (1)$$

In this equation, the effect of residual stresses is only included in the weld metal assessment and is accounted for by the factor $x \cdot b$ with the yield ratio $b = \sigma_{Ywm}/\sigma_{Ypl}$. In what follows, two basic cases are considered. For stress relieved welds, zero residual stresses are assumed: $x = 0$. For as-welded weldments containing a longitudinal crack and therefore, subject to the transverse residual-stress component, two levels of residual stresses are chosen, *i.e.*, $x = 0.2$ and $x = 1$. The value of $x = 0.2$ is included to evaluate the situation of stress-relieved welds where no complete stress relief may have been achieved. For the design situation where $a = 2/3$ (SCF = 1), the $CTOD_{wm}$ values for various combinations of base and weld metals are shown in Table 1. Here, it should be noted that the assumed material properties in Table 1 represent typical values of North Sea offshore platform weldments.

The calculated values indicate that lower weld metal CTOD requirements relative to the base metal CTOD can be specified for stress relieved weldments, and the higher the degree of overmatch is, the lower the $CTOD_{wm}$ may be. For the as-welded condition, however, much higher $CTOD_{wm}$ values are required.

The results of this simple assessment show, irrespective of the crack dimension and plate thickness, that the CTOD design curve approach incorporates the expected protective effect of weld metal overmatching on weld metal CTOD in stress relieved welds. When some allowance for residual stresses is included in the CTOD analysis, the weld metal CTOD values are much higher than those required for the base metal. The latter prediction is often in contradiction with the results of wide-plate test on as-welded specimens (Refs. 8, 9), *i.e.*, the protective effect characteristic for overmatching weld metal is also effective in as-welded weldments. This conflicting experience is not too surprising for the simple reason that the CTOD design

Table 1—Effect of Weld Metal Matching on the Required Weld Metal CTOD for Various Degrees of Overmatching

Material Properties			$CTOD_{Weld\ Metal}/CTOD_{Base\ Metal}$		
σ_{Ypl} [a]	σ_{Ywm} [b]	OV (%) [c]	σ_R [d] $= 0$	$\sigma_R = 0.2$	$\sigma_R = \sigma_Y$
350	520	49	0.71	1.42	2.49
	490	40	0.76	1.43	2.44
420	520	24	0.86	1.45	2.34
	490	17	0.90	1.46	2.30
480	520	8	0.95	1.47	2.25
	490	2	0.99	1.48	2.21

(a) Base metal yield strength.
(b) Weld metal yield strength.
(c) Residual stress.
(d) $(\sigma_{Ywm} - \sigma_{Ypl})/\sigma_{Ypl}$.

curve is a simple one-parameter approach that was not developed to cover the specific problem of weld metal overmatching (Ref. 7).

The preceding observations and the very fact that the CTOD requirements generate much controversy emphasize the need to examine the fundamentals underlying weld metal CTOD or small-scale test requirements. This can be achieved by performing an examination of the deformation behavior of the composing parts in a weldment, and the strategy to be followed would consist of:

1) The development of an analytic model that relates the applied stress to the crack tip opening of a crack of known geometry using the stress-strain characteristics of the composing parts of a weld.

2) The validation of the predictions with actual test results obtained from a test configuration enables a proper assessment of the interaction between weld metal and base metal deformation behavior.

Large-Scale Testing

The preceding observations indicate that a suitable test is needed to develop refined weld metal requirements. This can be achieved by considering a test specimen of representative service dimensions that incorporates a number of associated factors having an important effect on weld joint performance. The factors that affect weld joint performance are related to the interaction of the different material properties present in welded joints, the different strain-hardening rates, the degree of crack tip constraint, the crack shape, size and orientation, the loading mode (tension versus bending) and the residual stress levels. Unfortunately, very little reference can be made to either experience or small-scale fracture test data bases to study the effect of those variables since these tests suffer from the adoption of an arbitrary test specimen design and of a loading mode.

Thus, in view of the many variables involved, it is obvious that a test configuration should be selected that takes account of and duplicates, as far as possible, the conditions of operation pertaining to the whole weldment under consideration. In this context, the cracked large-scale wide test specimen is a valuable means to generate the required reference information. Particularly, the wide-plate tension test is a good analogue of such structures as pressure vessels, pipelines, and ship hulls, where the loading is primarily membrane tension. However, its applicability to situations where the primary loading is bending requires more study.

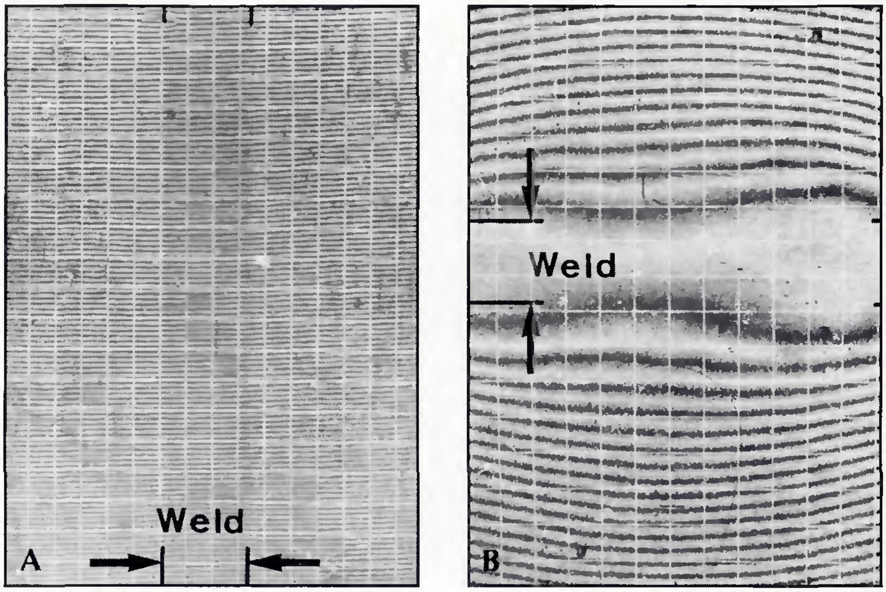


Fig. 1 — Moiré pictures illustrating the extent of plastic deformation in: A — A longitudinally loaded weldment; B — a transversely loaded weldment. Note: closer fringe spacing denotes higher strains

The Wide-Plate Test

The notched large-scale tension test (or the wide-plate test) is the only large-scale laboratory test that, provided the conditions for fracture initiation are adequately modeled, may provide a rational basis for the validation of small-scale test toughness requirements (Refs. 10–13). In this context, it must be remembered that throughout its development, the wide-plate test has often been used to verify or establish small-scale test performance requirements (Refs. 14, 15).

In as far as the validation of weld metal toughness properties is concerned, the wide-plate test is, in particular, a suitable means to obtain an improved understanding of the interaction between crack size, base metal, HAZ and weld metal properties. In addition, weld metal wide-plate test results may, for many applications, be easier equated with practice than the results and analyses of small-scale fracture mechanics tests. This philosophy is sometimes adopted in the application of a fitness-for-purpose approach to the assessment of low weld metal toughness problems encountered in small-scale testing (Ref. 16).

Although the wide-plate test specimen incorporates many desirable features, it is important to admit that such tests are expensive and that they will never reach the status of a routine test. On the other hand, when the wide-plate test is retained to solve low-toughness problems, it is of importance to note that major economic benefits can be achieved when account is taken of the costs involved in retesting, construction delays, over-specification, repair, etc. Despite this advantage, it must be emphasized that the wide-plate test may not be mistaken in its purpose with a small-scale test whose main functions are related to the reduction in testing costs or material/weld metal quality control or both. As a consequence, wide-plate testing should be primarily considered as an intermediate step in the preparation of small-scale test requirements.

Wide-Plate Specimen Design

The design of wide-plate specimens cannot be standardized in the same way as say, a CTOD specimen. The question as to which specimen design is best suited must be resolved by giving due consideration to the type of problem to be assessed. For this reason, various wide-plate specimen designs are available to study specific problems (Refs. 10, 12, 13). As Fig. 1 shows, a clear distinction must be made between longitudinally and transversely loaded joints.

The evaluation of either the longitudinally or transversely welded test specimen is complicated by the effect of the relative difference in strength of weld metal and surrounding base metal on weldment deformation behavior. The practical effect of this relative difference depends upon whether the weld metal is constrained to deform in the same manner as the adjacent base metal (Fig. 1A), or whether it is free to behave as a separate unit — Fig. 1B. Provided the applied stress is parallel to the weld, the former situation can be modeled by a wide plate containing a longitudinal weld, while the latter situation can be modeled by a transversely welded wide-plate specimen — Fig. 2. The effect of yield magnitude tensile residual stresses on a transverse weld can be incorporated in a cross-welded specimen that contains a

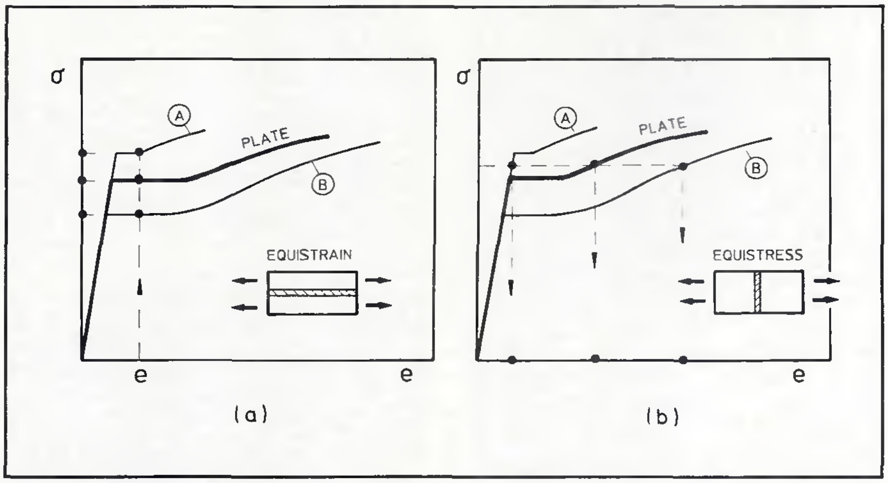


Fig. 2—Schematic representation of the effect of weld metal overmatching (Curve A) and weld metal undermatching (Curve B) on stress and strain distribution in: A—Longitudinally loaded weldment; B—transversely loaded weldment

longitudinal and a transverse weld. The variants shown in Fig. 3 permit various possibilities to be studied (Ref. 13).

Longitudinally Loaded Wide-Plate Specimens

A weld with its length parallel to the major stresses will be forced to yield and deform despite its overmatching (*viz.* undermatching) strength if the surrounding base metal starts to yield—Fig. 2A. The interest with the longitudinally welded specimen lies in the readiness with which the effects of longitudinal weld tensile residual stresses may be studied. Provided the plate width is sufficiently large, the weld tensile residual stresses may reach yield-point magnitude.

Though the performance characteristics of both the single longitudinally and cross-welded specimens, in relation to the weld matching effects, will not be further investigated here, some brief comments are in order. The evaluation of the former consists essentially in the study of the combined effect of crack size and toughness distribution along the crack tip on the deformation behavior of the weldment, *i.e.,* a Kinzel type of test (in which the crack samples the base metal, HAZ and weld metal) could well provide the required information—Ref. 13. With regard to the latter, the evaluation is very similar to that for a transversely loaded weld. In other terms, the combined effects of crack size, the degree of weld metal matching and weld metal toughness need to be incorporated in the assessment of those.

Transversely Loaded Wide-Plate Specimens

The deformation behavior of a weld with its length transverse to the major stresses depends on the weld metal yield properties. If the weld metal yield strength overmatches that of the base metal, weld metal yielding will not occur until the weld metal yield strength is reached, and extensive yielding and strain hardening of the base metal are normally required to cause plastic deformation in the weld metal—Fig. 2B. Depending on crack size, a weld metal crack will largely be protected from plastic straining. This protection, of course, will not take place when the weld metal is sufficiently brittle to lead to failure under elastic loading conditions or when large weld metal cracks are present. The obvious conclusion is that crack size is a key factor with regard to the apportionment of plastic deformation in such weldments, and this issue will be discussed in more detail in the following sections.

Evidently, the expected beneficial effects associated with weld metal overmatching will not apply to situations where the weld metal undermatches the base metal since most of the applied strain will be concentrated in the weld metal. The practical implication is that undermatching weld metal will need vastly increased toughness properties in order to obtain satisfactory weld joint performance and that particular attention must be given to areas where they are used (*e.g.,* repair welding—Ref. 2).

Evaluation of a Tranversely Loaded Wide-Plate Test Specimen

When analyzing the deformation behavior of a tension-loaded, transversely welded, crack-free wide-plate specimen, it should be kept in mind that, although the nominal/applied stress across all regions of the specimen is the same, the nominal strains in those regions may be different—Fig. 2B. Another important point to consider is that, irrespective of the presence of a weld metal crack, when the weld metal yield strength overmatches that of the base metal, the load-extension behavior of the whole welded joint will be governed by that of the base metal (Ref. 16).

A weld metal crack will modify this deformation pattern and a nonuniform elastic-plastic strain distribution in the otherwise uniformly elastic strained weld metal will occur. In this way, four different deformation modes of fracture behavior can develop (Fig. 4): 1) elastic behavior, 2) elastic-plastic behavior, 3) net section yielding (NSY) and 4) gross section yielding (GSY). The occurrence of one or the other deformation mode, as well as the extent of plastic deformation, depend on a number of factors. The most significant ones are the test temper-

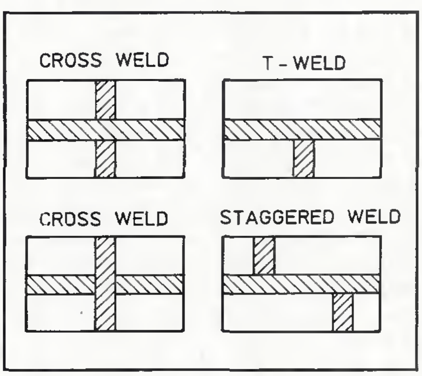


Fig. 3—Some typical wide-plate configurations for modeling practical weld details

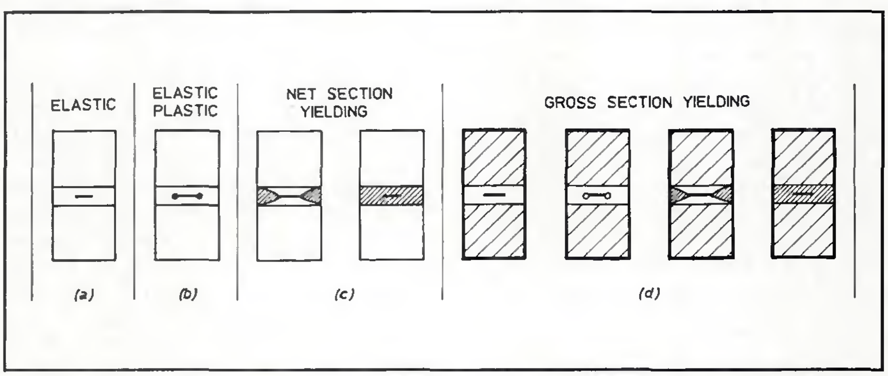


Fig. 4—Schematic representation of the various deformation modes in tensile loaded weldments

ature, the magnitude of the applied stress, the degree of weld metal overmatching, the strain-hardening characteristics of the weld metal and the size of the crack. From a macroscopic point of view, the four deformation modes can be recategorized in two basic types. At fracture, the applied stress is either elastic or exceeds the yield strength of the base metal. In the latter case, it is evident that plastic deformation in the base metal will occur — Fig. 4D.

Weld Metal Crack Acceptance Criterion

The evaluation of the criticality of a weld metal crack depends on the deformation mode achieved in the weld metal. For the elastic and the elastic-plastic or contained yielding deformation modes, the fracture mechanics principles can be applied. For the situation of uncontained weld metal yielding (Figs. 4C and D), the limit analysis or plastic collapse principles could be used.

The next factor that needs to be considered is related to the weldment performance requirement. From an engineering point of view, it may be appropriate to consider a high confidence performance level with respect to the acceptability of the test result. When it is intended to assess the situation in which a structure may be accidentally subjected to plastic strains in service (overloading) or when it is assumed that significant plastic strains can be accommodated (*e.g.*, during pipe laying), it is practical to require gross section yielding (GSY) as a demonstration of satisfactory performance.

Gross Section Yielding (GSY) Method

The question of how much (elastic and plastic) strain should be required depends on the fracture control requirement. On the other hand, it must be noted that the achievable overall strain or the strain measured away from the crack is a function of the base metal mechanical characteristics, the crack shape and size, the strain-hardening rate of the net section area, the test temperature and the degree of weld metal overmatch.

The first performance criterion related to fracture control in a wide-plate test specimen was established in the early 1960's. The wide-plate test results were validated by comparing the gross strain, measured over a considerable gauge length, to a semi-arbitrary pass/fail gross strain level of 0.5% (Refs. 14, 15). This level corresponds to about four times the yield strain of the steels used at that time and was derived from the experimental observations that the plastic strain with a safety factor of about 2.5, at a nozzle with a SCF of about 2.5 loaded to 1.3 (hydraulic pressure test) × ⅔ yield pressure test conditions is about that value

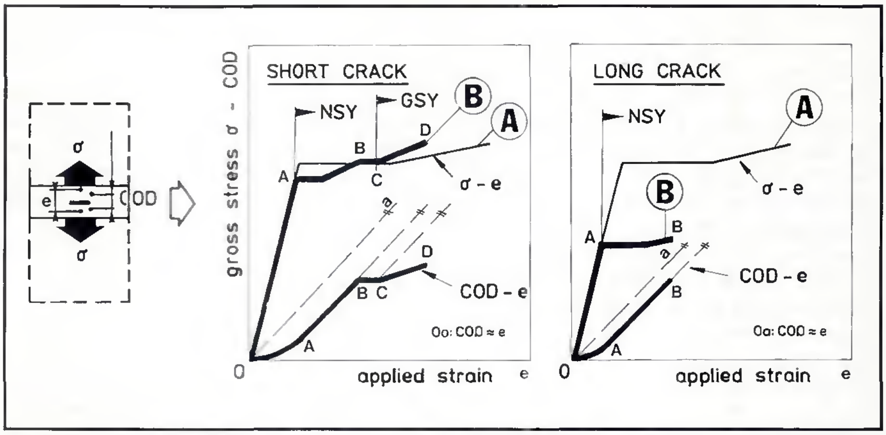


Fig. 5 — Interaction between the weld metal stress-strain and COD strain curves of a weld metal containing a short or a long crack, respectively. Curve A — Weld metal stress-strain curve; Curve B — stress-strain curve of weld metal with through-thickness crack

(this criterion was also chosen as a safe measure to draw up Charpy impact requirements for pressure vessels and storage tanks — Ref. 15). Because the four-times-yield-strain criterion was developed to provide an answer for a particular problem, it might be noted that for other applications, such as for higher strength steels, the four-times-yield criterion could be either a too severe or a too restrictive requirement.

The need for a more practical engineering and consistent means for assessing either elastic/plastic or plastic wide-plate test performance was solved by the development of the GSY concept in the early 1970's (Refs. 17, 18). The concept rests on the idea that when the material at the crack tip can sufficiently strain harden to compensate for the missing cross-sectional area in the plane of the crack, the applied plastic strain can be (uniformly) distributed all along the specimen length prior to failure. As such, the GSY criterion is conceptually different from a fracture-mechanics-based assessment to brittle fracture safe design, but the criterion can be considered as a logical extension of conventional fracture-mechanics concepts since the wide-plate test results can readily be assessed in pass/fail terms. In addition, the adoption of the GSY requirement is a particularly convenient measure to verify whether a representative crack can be safely left (fail/pass) in the structure, while it offers the possibility to evaluate failure from two aspects, *i.e.*, brittle fracture associated with an adequate level of prefracture strain and plastic collapse.

Since the GSY criterion is almost entirely empirical in its practical application, it is not required that certain assumptions are made concerning weld residual stresses, local peak stresses, etc., in its application. To distinguish between contained or net-section yielding (NSY) from GSY, it is only needed to make a direct comparison between the uniaxial yield strength of the (base) material and the gross section fracture stress (*i.e.*, the load at fracture divided by the cross gross section) at the temperature of interest. In case of transversely loaded weldments, GSY is achieved when the gross section fracture stress exceeds the yield strength of the base metal. Provided the weld metal overmatches the base metal in yield strength, it is thus possible to merge the well-established fracture mechanics relationships and the requirement of GSY.

For all the reasons discussed, and as the author considers the GSY to be a realistic requirement, it is thus reasonable to adopt the GSY requirement during the further discussion.

Relationship between COD and Applied Strain, Analytical Modeling

In essence, the object of this section is to develop a simple analytical relationship between the crack opening displacement (COD) crack driving force for a fracture measured in a transversely welded cracked tension-loaded test specimen, the applied deformation for a given crack shape (though thickness or surface breaking), and the degree of weld metal overmatching for the case of GSY at fracture. Furthermore, the COD crack driving force is then equated to the weld metal CTOD fracture resistance to crack extension as measured in a standard CTOD bend test.

Weld Metal Behavior in Tension

Before the interaction between the COD and weld joint performance can be analyzed, we must know how the COD in the weld metal alone varies with the applied strain. The applied gross stress-strain (σ-e) and the crack opening displacement-strain (COD-e) curves shown in Fig. 5 model the sequence of events for a tension-loaded, through-thickness cracked weld metal. The interaction between these curves can be evaluated as follows:

1) Low stresses produce elastic weld metal extension and a small crack opening displacement. At higher stress levels, but still smaller than σ_{Yw}, a local plastic zone ahead of the crack tip will develop and a further increase of the COD will be produced (Fig. 5—line OA). The plastic zone corrected (Irwin adjustment) COD can then be obtained from the following equation (Refs. 16, 20–22):

$$\mathrm{COD} = \frac{\sigma^2 \cdot \pi \cdot a}{E \cdot \sigma_{fw}} \cdot \frac{1}{1 - \frac{1}{2}\,(\sigma/\sigma_{fw})^2} \quad (2)$$

in which σ_{fw} is the flow stress of the weld metal, a is the half crack length and σ is the applied gross stress. In Equation 2, σ_{fw} relates to the flow properties of the material (*i.e.*, the weld metal) controlling the extent of the plastic zone, while the effect of strain hardening on COD has been directly accounted for by replacing σ_{Yw} with σ_{fw}, which has a value about halfway between the yield and the ultimate tensile strength of the weld metal. Furthermore, it is assumed that the opposite effects caused by the occurrence of small plastic zones at the crack tips and the strain hardening on the COD are implied in Equation 2. Hence, Equation 2 provides a usable model to estimate the COD value for contained yielding situations. At stress levels approaching weld metal yield magnitude, a better quantification of those effects is needed. In this connection, it should be noted that alternative estimates of COD are possible, but their treatment is beyond the scope of this paper (Refs. 20, 21).

2) As the stress increases, the plastic zone ahead of the crack tip enlarges until NSY occurs. After the onset of NSY, the applied displacement is entirely transmitted to the crack tips and a linearity of the COD-e relationship becomes noticeable during the Luders straining phase—Fig. 5-AB. For long cracks, all the applied strain goes into the crack tips through the slip bands, and the shape of the COD-e curve remains unaltered until fracture occurs—Fig. 5-right side. For short cracks, a similar behavior is exhibited at the lower strain range (Fig. 5-AB), but at higher strains (Fig. 5-BCD), the slope of the COD-e curve will be lowered because of the strain-hardening effects in the weld metal.

3) When the strain hardening or the crack tip constraint increase the flow stress in the crack tip area, plastic strains may occur in the weld metal gross section, *i.e.*, GSY will develop. At the onset of GSY, the applied displacement or the gross strain e is absorbed by the remote uncracked sections of the weld metal and the COD remains constant during the Luders straining phase—Fig. 5-BC. Once GSY occurs, the applied displacement is distributed along the entire length of the weld and the COD increases slowly with e—Fig. 5-CD. Because of the apportionment of strain in the remote and net sections of the weld metal, the COD is no longer proportional with the strain e. The slope of the curve segment BCD is controlled by weld metal strain-hardening properties and the crack size.

Crack Shape Dependence of the COD Crack Driving Force

Since surface cracks are more common than through-thickness cracks, it is of practical importance to assess the shape of the COD-e curve for this situation. In order to ensure consistency with Equation 2 and to ease the mathematics associated with the evaluation of such a crack, Equation 2 can be generalized by means of a crack geometry correction factor g. For cracks other than through-thickness ones, Equation 2 can be adjusted by substituting the factor a representing the half crack length by the factor $g^2 \cdot t$ in which t is the crack depth:

$$\mathrm{COD} = g^2 \cdot \frac{\sigma^2 \cdot \pi \cdot t}{E \cdot \sigma_{fw}} \cdot \frac{1}{1 - \frac{1}{2}\,(\sigma/\sigma_{fw})^2} \quad (3)$$

The crack shape correction factor g for surface cracks can, when compared to the Newman-Raju analysis (Ref. 22), conveniently be approximated to within 5% by the Dufresne correction factor (Ref. 23):

$$g = 1.14 - 0.96\, t/l + \frac{(t/B)^2}{0.2 + 4.9\,(2t/l)^{1.2}} \quad (4)$$

in which B is the plate thickness, l the total crack length and t is the crack depth. If we now return to Fig. 5, it can be verified that with the applied stress being the same, the elastic COD for a surface crack will be smaller than for a through-thickness crack of the same length. As a further consequence, it is important to note that the position of the entire COD-e curve will be lowered because of the reduced constraint to plastic flow exhibited by a surface crack. For deep cracks, there is a small difficulty associated with Equation 3 in that the crack tip plastic zone may extend through the uncracked ligament behind the surface crack towards the back face of the specimen (ligament yielding—LY). Widespread yielding invalidates the application of Equation 3 and the ligament plasticity causes the COD to increase with applied stress at a higher rate than before LY. For the present purposes, the COD due to LY and beyond will not be considered so that the g factor remains usable until the onset of LY, *i.e.*, for $\sigma < [1 - t/B] \cdot \sigma_{fw}$ (Ref. 19). It should be noted that the COD during LY can be calculated using the solution given by McHenry, et al. (Ref. 21). After NSY of the whole cracked section and for stresses above NSY (*i.e.*, for GSY), the interaction between COD and e will, depending on the crack size, be similar to that described for the case of through-thickness cracks.

At this stage, it should be pointed out that the assessment of the deformation behavior in case of a HAZ crack is more complicated. However, as long as the plastic zone is small enough to be contained within the HAZ, the same principles of analysis apply.

Weld Joint Behavior in Tension

The analytic relation between COD and e for weld metal only, Equation 2 or 3, provides now the basis to predict the effect of overmatching weld metal yield strength on weld joint performance in the event that the degree of overmatching and the acting stress or strain are known. Since a welded joint consists of two different materials (abstraction is made of the HAZ region) having their own stress-strain characteristics, a distinction is to be made between a cracked and an uncracked weldment—Fig. 6. Because of the overmatch, the (uncracked) weld metal stress-strain curve, Curve A, lies above the stress-strain curve of the base metal, Curve C. When the weld metal contains a crack, yielding of the net section occurs at a stress below the uniaxial yield strength of the weld metal. As a consequence, the position of the cracked weld metal stress-strain curve differs from Curve A. Its position, Curve B, in relation to that of the weld metal or that of the base metal, depends on the crack size. For the purpose of the present discussion, Curve B is positioned between Curves A and C (Fig. 6), whereas, as pointed out earlier, the stress-strain curve of the whole (cracked) welded joint will coincide with that of the base metal, Curve C—Fig. 6. Hence, only the Curves B and C (Figs. 6 and 7) are of direct interest to characterize weld joint performance in the presence of a weld metal crack. If we recall that in a transversely loaded weld, the applied stress on each cross-section is the same while the acting strain in each of these sections is different, the interaction between COD and e can be evaluated as follows—Fig. 7:

1) For applied stresses up to the base metal yield magnitude, the COD can be calculated by means of Equation 2 or 3, and its value is represented by point E.

2) With further straining, the weld joint stress-strain response is characterized by Curve C. During the Luders straining phase (plateau EF), the COD will not increase and the corresponding COD-e curve is represented by a hori-

zontal line EF. It should be noted that the strain at point F can be as much as the Luders strain, and this can amount to 1% and beyond.

3) A subsequent increase in stress will provoke both a further elastic straining of the weld metal (portion EA on Curve B) and strain hardening of the base metal (portion FG on Curve C). The COD-e response is then characterized by curve OEFA. When fracture occurs at point A (*i.e.*, elastic fracture of the weld metal), the fracture strain of the weld joint will be as much as e_A.

4) If the weld metal toughness is high, the shape of the weld metal σ-e curve will be similar to that of Fig. 5 (short crack, Curve B). The displacement imposed at the specimen ends will then be apportioned: both plastic straining of the base metal and crack tip opening will be produced. The COD-e curve can take one of the following shapes: 1) when fracture occurs at C (Curve B, Fig. 7), the corresponding COD-e curve is represented by OEFAC and, 2) when fracture occurs at D (Curve B, Fig. 7), the corresponding COD-e curve is represented by OEFACD.

With changing position of Curve B, a similar analysis can be performed. For instance, for larger weld metal cracks, the position of Curve B will be lowered. This situation represents also the case, the crack length being unaltered, of a lower degree of overmatching or even undermatching. Particularly, when Curve B lies below Curve C (Fig. 5, long crack), it can be readily verified by means of Fig. 7 that weld joint performance can be very poor since all the applied strain goes into the crack tip.

Practical Significance of the Relationship between COD and Overall Strain

Previous considerations have illustrated that the weld metal yield strength is an important parameter because it controls strongly the COD crack driving force. Thus, the amount of weld metal yield strength overmatching, as well as crack size, are important factors to protect the weld metal crack from severe plastic strains.

Given Equations 2 and 3, and if we accept the compensating error mentioned earlier, it is possible to calculate, for stress relieved welds, the COD for the following examples. If the base metal yield strength (σ_{ypl}) of a 50-mm (2-in.) thick weldment containing a through-thickness crack of 25 mm (1 in.) is 350 N/mm^2 (50 ksi) and provided that the weld metal flow stress (σ_{fw}) is equal to 560 N/mm^2 (80 ksi), with $\sigma_{Yw}/\sigma_{UTSw}$ = 520/600 N/mm^2, the COD for an applied stress of 360 N/mm^2 implying the occurrence of GSY is, Equation 2, 0.055 mm. It should be noted here that the error on this value is negligible for the input data considered; it could well be so that the COD value is overestimated since the plasticity effects caused by a stress level of 0.69 (= 360/520 N/mm^2) are small indeed. When, in the previous example, the value of σ_{Yw} is reduced from 560 N/mm^2 to 460 N/mm^2 ($\sigma_{Yw}/\sigma_{UTSw}$ = 400/520 N/mm^2), *i.e.*, if the degree of overmatching is reduced from 49% down to 14%, the COD crack driving force increases from 0.055 mm to 0.077 mm. Similar calculations can demonstrate that an increase of crack size will cause a similar effect on the COD like a reduction of the degree of weld metal overmatch does.

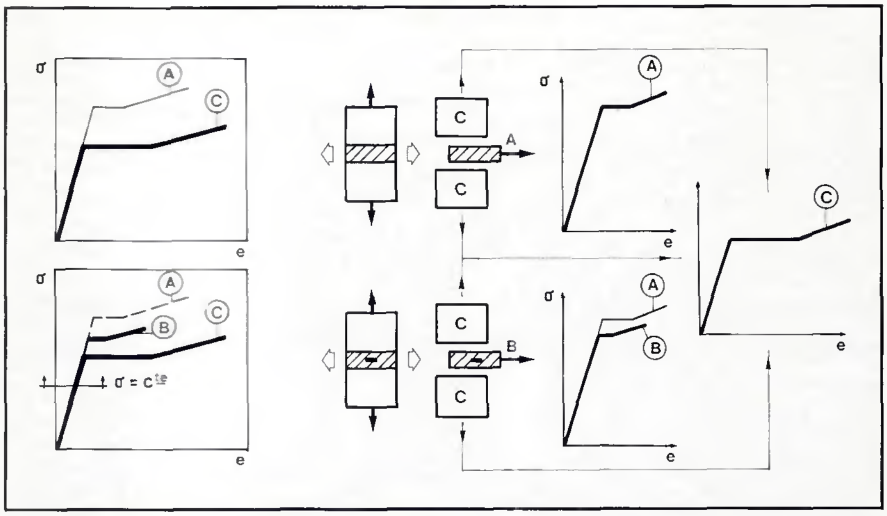


Fig. 6 — Weld metal (Curve A) and base metal (Curve B) stress-strain curves of a crack-free and cracked weldment for weld metal overmatched in yield strength. Curve B is the stress-strain curve of the weld metal

For the situation of a surface crack having a depth of 5 mm (0.2 in.) (10% of plate thickness) and length/depth ratios of 20:1 (length 1 = 100 mm/4 in.), 10:1 (1 = 50 mm/2 in.) and 5:1 (1 = 25 mm/1 in.), the COD levels to achieve GSY at a stress level of 360 N/mm^2 are 0.027 mm, 0.025 mm and 0.020 mm, respectively.

Even if one argues that the opposite effects of crack tip plasticity and strain hardening on COD in Equations 2 and 3 are not correctly accounted for, the numerical examples given suggest that for stresses below σ_{Yw}, but which produce GSY, the COD crack driving force for fracture will be small. However, larger COD values, and thus lessened protection from overmatching, will be

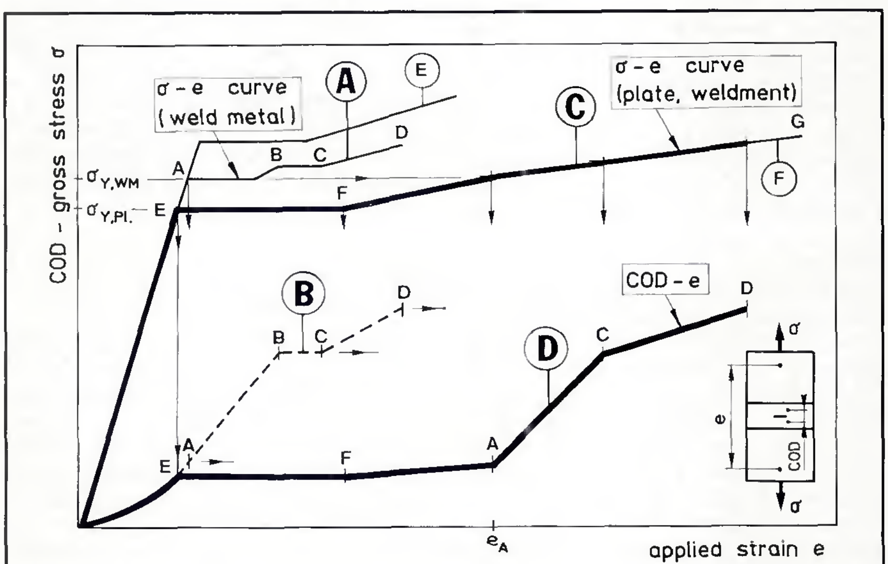


Fig. 7 — Schematic representation of gross stress σ and COD dependence on gross strain e in a weld metal cracked tensile loaded wide-plate specimen. Curves A, B and E are the weld metal stress-strain and COD strain curves. Curves C, D and F are the weldment stress-strain and COD strain curves

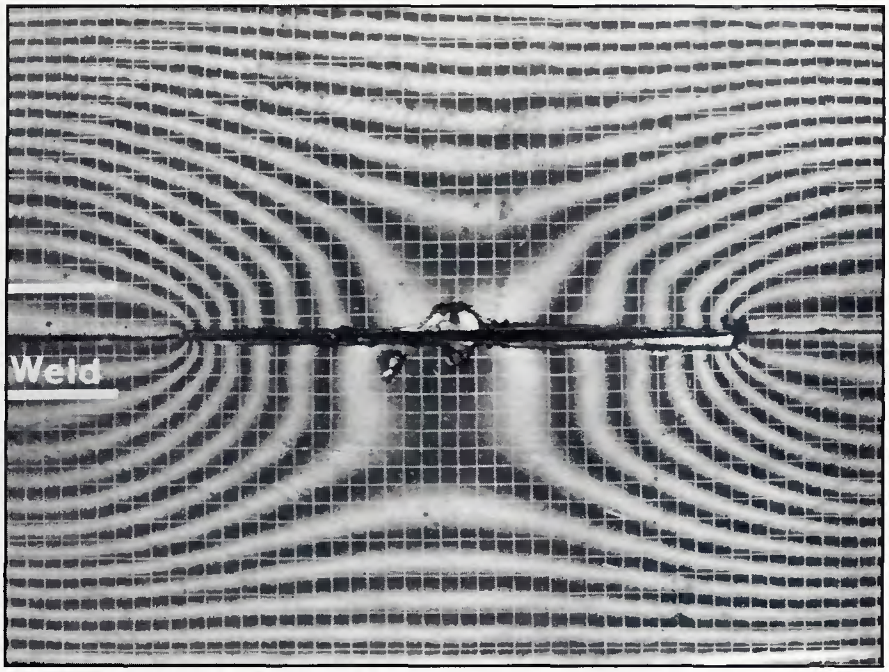


Fig. 8—Moiré fringe pattern visualizing the extent of plastic deformation in a 50-mm-thick weldment containing a prefatigued weld metal surface crack of 160 × 18 mm. Note: closer fringe spacing denotes higher strains

obtained for larger crack sizes. Similarly, at higher stresses or at large plastic strains in the base metal, ligament or NSY yielding can occur, and the computed COD values will diverge from the actual occurring COD values.

The next step in appreciating the practical significance of the relationship between the COD and applied strain e consists in comparing the difference between the crack tip opening displacement (CTOD), as measured in the (highly constrained) three-point bend test, and the crack driving force for fracture (COD), as measured in a tension mode of loading. Because of the reduced constraint associated with the latter, crack opening can more readily occur, and the COD crack driving force will be larger than the CTOD (Ref. 10). This implies that more crack tip toughness will be available than predicted by the CTOD bend test. In other words, when a CTOD fracture toughness level of 0.25 mm (which is typical for offshore applications) is specified, one can easily deduce, with the help of Fig. 7 together with the information obtained from the above examples, that for cracks of the given sizes located in overmatched weld metal, fracture in a transversely loaded weldment may occur at a strain level of 1% or higher. Since that amount of strain is not necessarily needed, it can already be concluded here that more attention should be given to the favorable effects associated with the use of overmatched weld metal and that the commonly specified weld metal CTOD requirements should be reassessed.

Experimental Work

The validity of the above findings has been verified on several occasions by performing wide-plate tests on transversely loaded welded joints containing either through-thickness or surface weld metal cracks (Refs. 24-26). In the following, a selection of some complementary wide-plate test data is presented together with the corresponding small-scale test data, namely CTOD, Charpy V-notch energy, and yield and ultimate tensile strengths at the temperature at which the wide-plate tests were executed. Particularly, the results obtained on (a) a 50-mm-thick butt joint welded wide-plate specimen in a BS 4360 Grade 50E steel and (b) a girth welded and curved wide-plate test specimens, extracted from steel line pipes in API 5LX65 of 22-mm (0.9-in.) wall thickness are reported (Ref. 26).

Test on Welded Butt Joint in a 50-mm-Thick Plate

Space does not permit one to give the full weld details. The following information, however, suffices to appreciate the test result. The material was a normalized steel with a yield strength of 364 N/mm^2 (52 ksi). The plate was welded by the SMAW process with a heat input of 2.3 kJ/mm using a single-V preparation. All testing was performed in the as-welded condition. The weld metal tensile properties were: $\sigma_{Yw}/\sigma_{UTSw}$ = 529/593 N/mm^2 (75/85 ksi) *i.e.*, the degree of weld metal overmatching was 45%. The weld metal had a Charpy V-notch energy of between 8 and 24 J at −40°C (−40°F), while the CTOD properties at −10°C (14°F) were 0.02/0.05/0.14 mm (B × 2B) and 0.04/0.15/0.21 mm (B × B). The wide-plate panel was 800 mm wide and 1000 mm long (31.5 × 39 in.). Test temperature was −10°C. The specimen contained a fatigue-sharpened surface crack 160 mm long × 18 mm deep (6.3 × 0.7 in.) located in the weld metal. The specimen did not fracture at an overall strain of 2.9% (gauge length 800 mm). The stress at the end of testing was 410 N/mm^2 and the COD, measured at the plate surface, was 2.9 mm corresponding to a crack tip opening of approximately 1.0 mm. The moiré picture reproduced in Fig. 8 provides evidence that GSY occurred.

Tests on Pipeline Girth Welds in API 5LX65 Steel Pipe of 22-mm Wall Thickness

The pipe material had a yield strength of 490 N/mm^2 (70 ksi). The girth welds were made with either the automatic GMAW or manual SMAW welding process. The degree of weld metal overmatching was 53% and 35%, respectively. The minimum Charpy V-notch impact properties at −40°C were 60 J (GMAW) and 18 J (SMAW). The minimum weld metal CTOD toughness properties (specimen geometry: B × 2B) at −10°C were 0.07 mm (GMAW) and 0.12 mm (SMAW); at −40°C they were 0.03 mm (GMAW) and 0.09 mm (SMAW). The curved wide-plate specimens were 300 mm wide and 900 mm long (12 × 35 in.). Note that the pipe curvature was retained in the specimen. The wide-plate tests were conducted at −10°C and −40°C. In total, some 40 wide-plate specimens were tested. They contained either (artificial) fatigue-sharpened surface cracks in the weld metal or buried natural (*i.e.*, moisture porosity, shielding porosity, incomplete penetration, incomplete fusion) weld metal discontinuities. The surface cracks were about 50 mm (2 in.) long × 6 to 10 mm (0.24 to 0.40 in.) deep, while the buried discontinuities were 300 mm long × 6 mm high. All test results showed that GSY occurred at overall strain levels in excess of 3 to 5% (gauge length 400 mm/16 in.) (Ref. 26). A typical moiré picture obtained during the course of this investigation is reproduced in Fig. 9. Note that the strain concentration in the weld area is caused by the ductile fracturing process. Figure 10 shows two photographs of a typical fracture face and a detail of a fatigue-sharpened crack.

Discussion of Test Results

The results of the experiments on as-welded wide-plate test specimens containing cracks in overmatched weld metal and loaded in tension have demonstrated that low weld metal toughness (both in terms of Charpy V-notch impact toughness and CTOD fracture toughness) can give adequate weld joint performance. These results revealed further that in an overmatched transversely loaded weldment, not all of the imposed deformation will necessarily be concentrated at the crack tip, and that the combined effects of weld metal yield strength overmatching, crack size and strain hardening can cause plastic straining or gross section yielding to occur away from the cracked weld metal cross-section. Furthermore, the results of the experiments demonstrated that the definition of either small or large cracks has a relative meaning. For example, recall that a weld metal surface crack of 160 × 18 mm in a 50-mm-thick weldment gave GSY.

Summary

The results of the present study provide incentive for a further in-depth quantitative assessment of the weld metal overmatching effects on both weld joint performance and weld metal fracture toughness requirements. The elements relevant to perform such an assessment involve both the development of a fracture mechanics model that relates the degree of weld metal overmatching, the applied load (deformation), crack size and COD crack driving force, and experiments to establish the validity of the analytic model.

Performance requirement—From an engineering point of view, the gross section yielding requirement assures adequate weldment performance and is thus a suitable criterion fit to establish weld metal toughness requirements.

The GSY requirement not only provides a large safety margin, in terms of straining capacity, against fracture, it is also characterized by an apportionment of the applied deformation into crack opening displacement and plastic straining of the remote material regions. For transversely loaded weldments, the apportionment of the applied deformation will be facilitated by using overmatching weld metals. This also means that the fracture behavior of a cracked weld metal does not solely depend on the weld metal fracture toughness.

These benefits cannot be claimed when fracture occurs for either the contained or net section (NSY) mode of yielding. In those cases, the COD crack driving force for fracture is directly proportional to the applied deformation, *i.e.*, the fracture safety for both the contained and NSY mode of yielding depends entirely on the crack-tip toughness. The latter might be an unreliable feature in high-performance structures.

The occurrence of contained, NSY or GSY yielding depends essentially on crack size, degree of overmatching, crack-tip constraint and strain hardening. High weld metal strain-hardening properties, yield elevation by constraint, short cracks and a high degree of weld metal overmatching are favorable to develop GSY. For weld metals having a moderate strain-hardening capacity, for long and deep cracks and for weld metals with a low degree of yield strength overmatch, GSY cannot occur. In the latter case, the deformation mode at fracture will be either contained or NSY. From a practical point of view, it is obvious that one must be assured that adequate weld metal overmatching is available because this simple measure contributes to the occurrence of GSY. For the time being, and until more experimental evidence becomes available, it is felt that a weld metal yield strength overmatch of some 20% relative to that of the base metal in transversely loaded weldments would already protect weld metal cracks from severe plastic strains.

Analytical modeling—The analytical modeling of a cracked tension-loaded weldment has illustrated that the effect of weld metal overmatching on COD crack driving force can be incorporated into the GSY performance requirement. The physical interpretation developed during this study indicates that for relatively small COD crack driving forces, GSY may easily be obtained. This interpretation holds only when contained plasticity occurs in

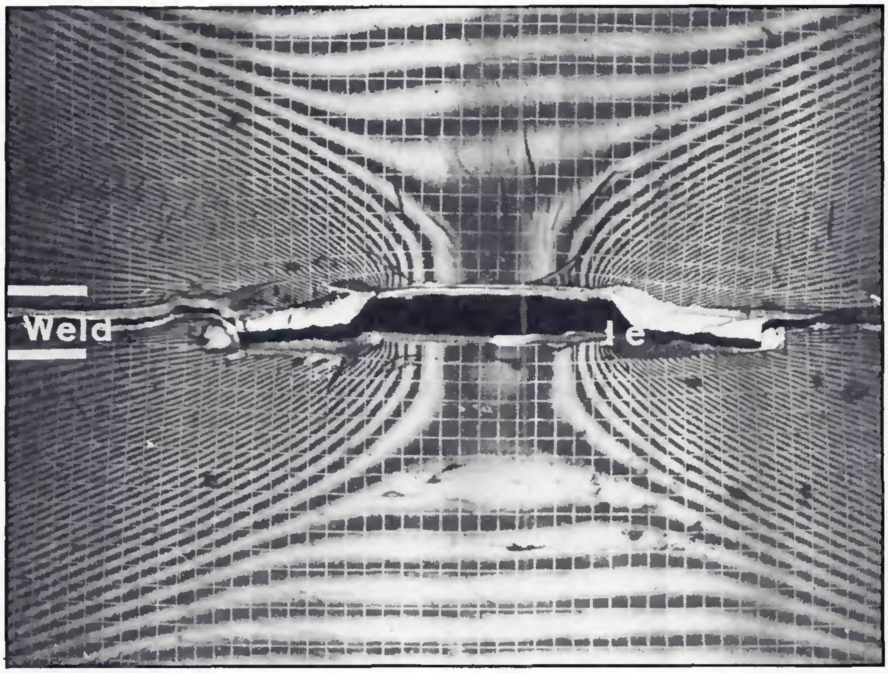
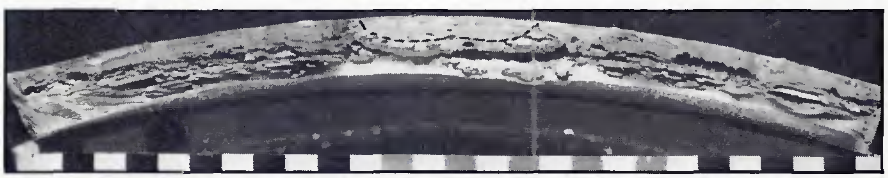


Fig. 9—Moiré picture of wide-plate test specimen described in Fig. 10. Note: the high density of fringes along the fracture path are caused by the ductile fracturing process



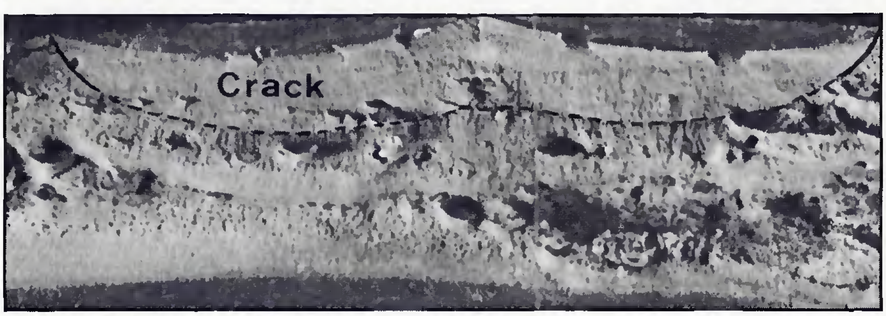


Fig. 10—Typical fracture surface of curved wide-plate specimen. Crack size is 55 × 10.1 mm. Test temperature was −40°C. Strain at fracture was 6.4% (CTOD = 0.07 mm)

RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT/RESEARCH/DEVELOPMENT the weld metal; the present analysis is thus not adequate for general application and further refinements are needed to incorporate the situations of ligament yielding (surface cracks), NSY and residual stress effects.

However, though ligament yielding causes the COD driving force to increase with applied strain at higher rate than before ligament yielding, the experimental data have further demonstrated that the crack driving force for fracture, in the presence of relatively large cracks giving GSY, was several times the CTOD fracture resistance. This finding illustrates that relief of geometric constraint is also a key factor in estimating fracture resistance.

Experimental assessment— Although the conventional three-point CTOD bend test is a valuable elastic-plastic fracture mechanics parameter for the assessment of crack severity in brittle materials, it must be admitted that the three-point CTOD bend test gives merely information on the local crack tip fracture toughness. Hence, the weld metal fracture toughness, as measured in a CTOD test, may ignore the beneficial effect of weld metal overmatching on the strain pattern in and around the weld. In addition, it should be noted that the use of the CTOD design curve to quantify precisely the effect of weld metal overmatching on weld joint performance may produce overly pessimistic CTOD requirements in the sense that the COD driving force for fracture is overestimated (recall that at the time of the development of the design curve concept, no consideration was given to the particular effects associated with weld metal matching).

This study has shown that the potential advantages that might accrue from the use of weld metal overmatching on both weld joint performance and tolerable crack size, and thus the required toughness, must be evaluated by a test configuration that incorporates the various factors that affect weldment behavior. As such, the tension-loaded wide-plate test can be used to simulate structural behavior of an important number of structural details and to treat the recurring problem about weld metal toughness requirements on a laboratory scale. Unfortunately, the costs involved in performing wide-plate test precludes its general application.

Therefore, for weldments in which the combined effects of weld metal overmatching and crack size have a prodigious effect on the COD crack driving force, an alternative small-scale specimen design should be developed that can readily simulate the difference between the strength of the base metal and the weld metal, and the degree of constraint experienced by weld cracks. In this context, the study of a four-point bend CTOD test merits serious consideration since this test configuration permits the assessment of the interaction between the relative deformation capacities of the various regions in a weldment. Further virtues are simplicity in testing and the possibility to aid the interpretation of wide-plate test results (Ref. 3).

Conclusions

This study has shown that the strength of a transversely loaded weldment with weld metal cracks cannot be predicted by the performance characteristics of the base metal and the weld metal (or HAZ) alone but is a complex function of both. It has also been pointed out that the results of small-scale fracture toughness tests are extremely difficult to interpret because of the concomitant beneficial effects of weld metal overmatching on weld joint performance.

The role of the distinctive features associated with the interaction between weld metal yield strength overmatching, crack size, applied strain and toughness in determining the performance of weldments requires further study. Such a study would, in turn, provide the basic information to establish a rational basis for weld selection and design. The information which is urgently needed is, among others, related to the following:

1) The study of the dependence of the COD crack driving force for fracture on applied load and crack size for various degrees of weld metal overmatching. In other words, research should be directed to determine the factors that determine the deformation behavior of weld metal (or HAZ) with the further aim of resolving the extent to which the mechanical and fracture toughness properties of this zone determines the performance of the weldment.

2) The development of a simple but suitable testing technique in which the advantages of weld metal overmatching on weld joint performance can be quantified. In a sense, tests of structural components or wide-plate tests should be encouraged in order to discover better small-scale test methods that provide an integrated index of weldment performance.

For the time being and apart from the foregoing observations, the most pertinent conclusion is the advantages of weld metal overmatching should be more precisely reflected in material design codes and specifications. Since the variation in base material yield strength supply range of modern steels, where the required yield strength is achieved by a thermomechanical treatment/accelerated cooling (TMCP) or quenching and tempering (QT), can amount to 25% of the minimum specified value, it is evident that an upper bound value of the base metal yield strength should be specified in order to maintain a minimum degree of weld metal overmatching in fabrication welds. In particular, when high-strength TMCP steels ($\sigma_Y > 420$ N/mm^2) are used, this requirement is a key factor to ascertain adequate weldment performance.

Acknowledgments

The author wishes to thank Prof. Ir. A. Vinckier, director of the Laboratory Soete for Strength of Materials, Rijksuniversiteit, Gent, Belgium, for his permission to publish this study. The financial support of the Instituut voor Wetenschappelijk Onderzoek voor Nijverheid en Landbouw (IWONL) and the National Fonds voor Wetenschappelijk Onderzoek (NFWO) is also gratefully acknowledged.

References

1. Satoh, K., and Toyoda, M. 1984. Applicability of bending COD test of welds for securing required fracture performance of welded structure. *Int. Institute of Welding, IIW* Doc. 1063-1984, Boston Annual Assembly.

2. Stern, I. L., and Alia, B. L. 1980. Materials, fabrication and inspection requirements for offshore fixed structures. *Proc. Offshore Technology Conference, Houston, Tex. 1980.* Paper 3743, pp. 71-82.

3. Walker, E. F. 1986. Fracture toughness testing—present status of Charpy V-notch impact and CTOD testing. *Proc. of the Symposium on the State of the Art in Materials Testing.,* K. VIV Antwerp, Belgium.

4. Burdekin, M., Dawes, M. G., Egan, J., Shackleton, D., and Widgery, D. The properties and requirements for weld metal in relation to failure by brittle fracture. *Int. Institute of Welding, IIW* Doc. X-506-69.

5. Dawes M. G. 1974. Fracture control in high yield strength weldments. *Welding Journal* 53(9):369-s to 379-s.

6. Harrison, J. D. The state-of-the-art in crack tip opening displacement (CTOD) testing and analysis. *TWI Research Report* 7302.10/80/210.2

7. Kamath, M. S. 1978. The COD design curve: an assessment of validity using wide plate tests. *Welding Institute Research Report* 71/1978/E; or 1981. The COD design curve: an assessment of validity using wide-plate tests. *Intern. Journal of Pressure Vessels & Piping* 9.

8. Denys R. 1985. Significance of CTOD in cross-welded loaded joints with weld metal overmatching in strength. *18th National Symposium on Fracture Mechanics,* ASTM, STP 945, Boulder, Colo., pp. 686-698.

9. Gulvin, T. F. 1979. Brittle fracture resistance of welded joints of some high-strength steels of medium thickness. *Proc. CEC Symposium Production and Use of Heavy Plate,* Luxembourg, Belgium, pp. 413-466.

10. Baker, R. G., Barr, R. R., Gulvin, T. F., and Terry, P. 1973. The use of wide plate test data for design against brittle fracture. *Proc. Pressure Vessel Technology Int. Conf.,* San Antonio, Tex., Ref. II.75, pp. 1049-1058.

11. Denys, R. M. 1982. The wide plate test and its application to acceptable defects. *Conf. Proc. Fracture Toughness Testing—Methods, Interpretation and Application.* London, England.

12. Pisarski, H. 1987. Philosophy of welded wide plate testing for brittle fracture assessment. *The Fracture Mechanics of Welds.* EGF Pub.2, Ed. Blauel and Schwalbe, Mech. Eng. Publications, London, England, pp. 191–208.

13. Denys, R. 1988. Wide plate testing of weldments. *ASTM Proc. of Symposium on Fatigue and Fracture Testing.* Reno, Nev., to be published.

14. Dawes, M. G., and Denys, R. M. 1984. BS 5500 Appendix D, An assessment based on wide plate brittle fracture test data. *Int. J. Pressure Vessel Piping* 15:161-192, and BS 5500 1984 Appendix D, Fusion welded pressure vessels for use in chemical, petroleum and allied industries—Part 1: carbon and ferritic alloy steels, recommended practice for vessels required to operate at low temperature.

15. Woodley, C. C., Burdekin, F. M., and Wells, A. A. 1964. Mild Steel for Pressure Equipment of Sub-Zero Temperatures. *Brit. Weld. J.* 11 (3):123-136.

16. Denys, R. M. 1987. Toughness requirements in transversely load welded joints—an evaluation based on wide plate testing. *The Fracture Mechanics of Welds.* EGF Pub. 2, Edited by J. G. Blauel and K.-H. Schwalbe, Mechanical Engineering Publications, London, England, pp. 155-189.

17. Soete, W., and Denys, R. 1976. Fracture toughness testing of welds. *Proc. of Conf. on Welding of HSLA (microalloyed) Structural Steels.* Rome, Italy. ASM, ISBN 0-87170-005-0, pp. 63-84.

18. Denys, R. 1984. Defect assessment based upon gross section yielding. *Proc. of the Conf. on Pressure Vessel Conference.* San Franscisco, Calif.

19. Reed, R. P., Kasen, M. B., McHenry, H. I., Fortunko, C. M., and Read, D. T. 1984. Fitness for service criteria for pipeline girth weld quality. *WRC Bulletin 296.*

20. McHenry, H. I., Read, D. T., and Begley, J. A. 1979. Fracture mechanics analysis of pipeline girth welds. *ASTM STP 668,* pp. 632–642.

21. Cheng, Y. W., King, R. B., Read, D. T., and McHenry, H. I. 1984. Post yield crack opening displacement of surface cracks in steel weldments. *Fracture Mechanics: 15th Symposium ASTM STP 833.* Ed. R. J. Sanford, pp. 666-681.

22. Newman, J. C., and Raju, I. S. 1984. Stress intensity factor equations for cracks in three-dimensional finite bodies. *ASTM STP 791,* Vol. 1, p. 238.

23. Dufresne, J. 1981. Probabilistic applications of fracture mechanics. *5th International Conference on Fracture,* Cannes, France, Vol. 2, pp. 517–531.

24. Musgen, B., and Denys, R. 1982. Auswirkungen fertigungstechnischer Einflussgrossen auf das Verformungs- und Bruchverhalten derBaustahle wahrend der verarbeitung und Anwendung. *Report for Forschungsbericht der Studiengesellschaft fur Anwendungstechnik von Stahl und Eisen.* Dusseldorf, West Germany, pp. 1–210.

25. de Koning, A. C., Denys, R., and Meek, J. 1985. Testing of 125-mm and 200-mm-thick low-strength carbon steel for the construction of a Tripod Tower Platform (TTP). *Proc. of the Conference on Welding for Challenging Environments,* Toronto, Canada, Pergamon Press ISBN 0-08-031866-5, pp. 191–204.

26. Lian, B., Denys, R., and Van de Walle, L. 1986. An experimental assessment on the effect of weld metal yield strength overmatching in pipeline girth welds. *Proc. of the Third Conference on Welding and Performance of Pipeline,* TWI, Cambridge, England.