EFFECTS OF WELD STRENGTH MIS-MATCH ON CTOD DESIGN CURVE

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ABSTRACT

The viewpoint of local strain was applied to a transverse welded wide plate with a crack in the weld metal. It can be shown that difference in the plastic properties of the weld metal and base material significantly affects both fracture toughness and crack driving force. An important conclusion is that showing the influence of mis-match weld joint only individually according to toughness or crack driving force is not sufficient for the assessment of structure integrity. Moreover, if the stress-strain-curve of base material and weld metal can be expressed as the linear train-hardening laws, a simplified CTOD design curve in revised formula may be obtained, which can serve for predicting critical loads, critical strains or critical crack length for the welded structures.

KEYWORDS

Mis-match, weld joint, toughness, crack driving force, CTOD, design curve

NOMENCLATURE

a = crack length
E = young's modules
E_t = tangent modules of stress strain curve on post yield
L = distance from center of crack to measurement point
H = half of wide of weld metal
σ = stress
ε = strain
M = mis-match factor (σ_{YW}/σ_{YB})
δ = crack tip opening displacement

Subscripts

B = base material

W = weld metal
Y = incipient net section yielding

INTRODUCTION

A welded joint may be simply regarded as compound material consisting of two characteristic regions, base material and weld metal, which have different stress-strain and toughness properties. In general, concerning the yield strength of the base material and weld metal, three cases can be distinguished. Even-matching is the yield strength of the weld metal σ_{YW} equals that of the base material σ_{YB},the term undermatching is used for the case of $\sigma_{YW}<\sigma_{YB}$ and overmatching refers to $\sigma_{YW}>\sigma_{YB}$.

The assessment of a crack in a weld metal with strength mis-match is influenced by two respects that are toughness and crack driving force. High strength of the weld metal may lead to lower tough as compared to low strength of weld metal. On the other hand, overmatching provides yield protection of the weld metal and results in crack driving force descending in weld metal crack. Similarity undermatching may result in improving the weld metal toughness, but it also causes strain concentration in the weld metal, results in crack driving force increasing. Because of the importance in assessment of welded structures integrity, many research work focus on the influence of mis-matching on fracture properties of a weld metal crack. Mis-matching on the toughness requirement for the weld joint with crack has been outlined in details on K.-H. Schwalbe(1992) and Y. W. Shi(1995).Some research work on mis-matching to metal crack driving force can be founded in detail by K.-H. Schwalbe(1993).

The crack tip opening displacement(CTOD) approach is a popular method for evaluating the integrity of welded structures. By comparing the CTOD test results from wide plate test. R. M. Denys(1987) demonstrated that the performance of wide plates cannot adequately be described using CTOD values solely. Design curve analyses (PD6493, 1991) relate the global strain to the CTOD of the crack. However, comprehensive strain studies show that an overmatching weld metal encounters substantially lower strains than the applied global strain. Therefore, design curve assessments tend to unduly great on the strain of weld metal, that is to say it does not consider the influence of the weld metal crack driving force decreasing. On the other hand, high strength of weld metal may cause descending of toughness of weld metal. Similar opposite conclusions were obtained in undermatch weld metals. Therefore, if we only individually consider mis-match on influence the toughness or driving force, it may result in unduly conservative or risky conclusion. It is necessary considering both crack driving force and toughness on reality structure's fracture property. In present paper, a revised CTOD design curve formula is given, which can reflect the influence of mis-match weld metal on the influence of both toughness and crack driving force.

EFFECT OF MIS-MATCHED WELD METAL ON CTOD DESIGN CURVE

Reviewing the development of CTOD design curve (M. G. Daws, 1980), although

CTOD design curve has some theory analytic base, it is an experience formula based on the tension test of the wide plate with a central crack. The CTOD design curve formula is as follows:

$$\phi = \frac{\delta}{2\pi\varepsilon_Y} = \left(\frac{\varepsilon}{\varepsilon_Y}\right)^2 \qquad \left(\frac{\varepsilon}{\varepsilon_Y} \le 0.5\right) \tag{1}$$

$$\phi = \frac{\delta}{2\pi\varepsilon_Y} = \frac{\varepsilon}{\varepsilon_Y} - 0.25 \qquad \left(\frac{\varepsilon}{\varepsilon_Y} \ge 0.5\right) \tag{2}$$

where ε represents the global strain on the measured point, and ε_Y represents the yield strain on homogeneous material.

In the condition of transverse welded wide plate having weld metal crack (fig. 1), the stress-strain property is changed owing to the influence of mis-matching. Overmatching may causes toughness of weld metal is lower than that of base materials. On the other hand, crack driving force descends in weld metal crack owing to base material deformation prioritized to weld metal, which provides yield protection of the weld metal. Moreover, in the condition of some case metal undermatching may improve weld metal toughness and cause crack driving force increasing in same time. Therefore, according to formulae (1) and (2), the crack tip opening distance δ can not adequately express the stress-strain statement of weld metal crack tip. In order to put the influence of mis-matching in CTOD design curve formula, global strain ε of the measured point A is replaced by weld metal joint strain ε_W, and yield strain ε_Y of measured point A is replaced by weld joint yield strain ε_{YW}. The formula is as follows:

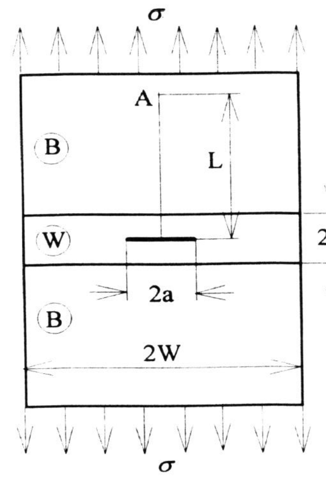

Fig. 1 Transversely welded wide plate containing a weld metal crack

$$\phi = \frac{\delta}{2\pi\varepsilon_{YW}} = \left(\frac{\varepsilon_W}{\varepsilon_{YW}}\right)^2 \qquad \left(\frac{\varepsilon_W}{\varepsilon_{YW}} \le 0.5\right) \tag{3}$$

$$\phi = \frac{\delta}{2\pi\varepsilon_{YW}} = \frac{\varepsilon_W}{\varepsilon_{YW}} - 0.25 \qquad \left(\frac{\varepsilon_W}{\varepsilon_{YW}} \ge 0.5\right) \tag{4}$$

In formulae (3) and (4), the weld joint yield strain ε_{YW} respects the influence of mis-matching on deformation capability of weld metal. Overmatching makes the deformation capacity decreased, which is $\varepsilon_{YW}<\varepsilon_{YB}$.On the contrary, undermatching makes the deformation capacity increased, which is $\varepsilon_{YW}>\varepsilon_{YB}$. On the other hand, the weld joint strain ε_W reflects the influence of mis-matching on weld crack driving force. Overmatching makes weld metal crack driving force decreased, which is $\varepsilon_W<\varepsilon_B$.It is said that when global ε is constant, the greater strain exists in base material and base material has a yield protect on the weld metal. Undermatching makes weld metal crack driving force increased, which is $\varepsilon_W<\varepsilon_B$.It is said that when global ε is a constant, the greater strain concentrates in weld metal. Thus, the formula (3) and (4) can represent fracture cases of the welded plate.

The relationship derived in this work is based on the following basic assumptions:

- Wide plate loaded transversely in tension
- Through-crack in weld metal
- Residual stress not considered
- Linear train-hardening behavior of base material and weld metal
- Plain strain conditions
- Infinitely large plate $a/W \rightarrow 0$

The following section will give local strain expression on each matching condition:

EXPRESSION OF WELD JOINT LOCAL STRAIN

Overmatch Weld Metal

Loading Range 1: $\sigma \le \sigma_{YB}$

Base material and weld metal are defomed below their respective yield strengths, and contained yielding conditions are present at a crack in either material region. In this condition, $\varepsilon_W=\varepsilon_B=\varepsilon$, that is:

$$\varepsilon_W = \varepsilon \tag{5}$$

It is to show that mis-match weld metal is not influence on the weld metal crack driving force.

Loading Range 2: $\sigma_{YW} \ge \sigma_{YB} \ge \sigma$

The base material deforms plastically, whereas the weld metal is still elastic

$$\varepsilon = \frac{\varepsilon_B(L-H)+\varepsilon_W H}{L} = \frac{(\frac{\sigma_{YB}}{E}+\frac{\sigma-\sigma_{YB}}{E_{TB}})(L-H)+\frac{\sigma_{YW}}{E}H}{L} \tag{6}$$

Solved,

$$\varepsilon_W = \frac{\varepsilon L-\frac{\varepsilon_{YW}}{M}(1-\frac{E}{E_{TB}}(L-H))}{H+\frac{E}{E_{TB}}(L-H)} \tag{7}$$

Loading Range 3: $\sigma \ge \sigma_{YW}$

Both the base material and the weld metal deform plastically

$$\varepsilon = \frac{\varepsilon_B(L-H)+\varepsilon_W H}{L} = \frac{(\frac{\sigma_{YB}}{E}+\frac{\sigma-\sigma_{YB}}{E_{TB}})(L-H)+(\frac{\sigma_{YW}}{E}+\frac{\sigma-\sigma_{YW}}{E_{TW}})H}{L} \tag{8}$$

solved,

$$\varepsilon_W = \frac{L\varepsilon-\varepsilon_{YW}(\frac{1}{M}-1)(1-\frac{E}{E_{TB}})(L-H)}{H+\frac{E_{TW}}{E_{TB}}(L-H)} \tag{9}$$

Undermatching Weld Metal

Loading Range 1 $\sigma \le \sigma_{YW}$

The base material and the weld metal are deformed elasticity.

ε_W is the same as eq.(5).

Loading Range 2 $\sigma_{YB} \ge \sigma \ge \sigma_{YW}$

The weld metal deforms plastically whereas the base material is still elastic

$$\varepsilon = \frac{\varepsilon_B(L-H)+\varepsilon_W H}{L} = \frac{\frac{\sigma}{E}(L-H)+(\frac{\sigma_{YW}}{E}+\frac{\sigma-\sigma_{YB}}{E_{TW}})H}{L} \tag{10}$$

solved,

$$\varepsilon_W = \frac{\varepsilon L-\varepsilon_{YW}(1-\frac{E_{TW}}{E})(L-H)}{H+\frac{E_{TW}}{E}(L-H)} \tag{11}$$

Loading Range 3: $\sigma \ge \sigma_{YB}$

ε_W is the same as eq.(9).

CONCLUSIONS

Overmatching of the weld metal may lead to lower tough as compared to even-matching and provide yield protection on section of the weld metal and result in crack opening driving force descending in weld metal crack. Similarity undermatching may result in improving the weld metal toughness, but it also lead to strain concentration in the weld metal, result in crack opening driving force ascending.

It is necessary that evaluating weld-crack fracture state from the effect of mis-match on the toughness and crack driving force.

The present study has proposed a revised CTOD design curve formula that can use to predicting critical load, critical strains, or critical crack length in homogeneous materials and mis-match weld structure.

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REFERENCES

British Standards Institution (1991), *PD 6493:1991, Guidance on Some Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures,* London.

Daws, R. G. (1980), The COD Design Curve, *In: Advances in Elasto-Plastic Fracture Mechanics* (L. H. Larsson ed.), 279-300, Applied Science Publishers, London.

Denys, R. M. (1987), Toughness Requirements in Transversely Loaded Welded Joints-An Evaluation Based on Wide Plate Testing, *In: The Fracture Mechanics of Welds*, (J. G. Blauel and K.-H. Schwalbe eds.), 155-189, Mechanical Engineering Publication, Bury St. Edmunds

Schwalbe, K. -H. (1992), Effect of Weld Metal Mis-Match on Toughness Requirements: Some Simple Analytical Considerations Using the Engineering Treatment Model (ETM), *Int. J. Fracture,* 56, 257-277.

Schwalbe, K. -H. (1993), Welded Joints with Non-matching Weld Metal-Crack Driving Force Considerations on the Basis of the Engineering Treatment Model (ETM), *Int. J. Fracture*, 62, 1-24.

Y. W., Shi (1995), Fracture Toughness Requirement of Mis-matched Weld Metals,*Int. J. Pres. Ves. & Piping,* 62, 201-204.