Near-tip Behavior of Ductile, Steady-State Crack Growth in a Hydrogen Charged Material

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Abstract

This study examines the influence of increased dislocation velocity due to hydrogen on the steady-state behavior of a crack propagating under quasi-static conditions in elastic-plastic, matched, over-matched, and under-matched weld materials. Finite element analyses in a small-scale yield setting with plane strain conditions resolve the near-tip fields under the remotely applied $K_I - T$ displacement fields. The constitutive model incorporates hydrogen induced dilation and softening effects on the inelastic behavior of the ductile material representative of a pressure vessel steel. Near the crack tip, the hydrogen concentration, triaxiality, and plastic strain depend on the remote loading, the extent of material softening, and the initial concentration of hydrogen in the weld and base metal. A simple measure of damage along the uncracked ligament predicts higher values of ductile void growth in the presence of hydrogen and implies lower resistance to crack advancement.

1. Introduction

The degradation of fracture toughness in common steels may limit the economical storage and transport of hydrogen using existing components built with current design standards. Welds join the majority of steel pressure vessel components and remain the most probable location of crack initiation with or without hydrogen present in the material. The structure may tolerate crack initiation in welds and subsequent (limited) crack growth. The results of this study describe the effects of local, crack-tip constraint on steel welds in the presence of hydrogen for slow, stable crack propagation. Under the conditions envisioned here, the diffusion rate sustains equilibrium of the hydrogen concentration ahead of the propagating crack tip and thus represents the classical Stage II regime of sustained load crack growth.

Burstow et. al. [1] demonstrate that constraint variations, arising from the combined effects of weld metal-base metal strength mismatch and from the remotely applied loading, influence strongly the near-tip fields ahead of a stationary crack. Lin et. al. [2] investigate the influence of weld-base material mismatch on the behavior of a single edge notched bend specimen and determine that the crack growth resistance curves decrease significantly in under-matched welds. Other researchers examine the influence of constraint on the behavior of steady crack growth with the computational framework proposed by Dean and Hutchinson [3]. Non-zero values of the *T*-stress reduce the near-tip fields ahead of a steadily propagating crack, as established by Varias and Shih [4]. In Niordson [5], highly over-matched welds lead to a significant reduction of the plastic zone size and a corresponding increase of the steady-state fracture toughness.

The presence of hydrogen modifies the continuum solutions for the near-tip fields by changing the local micromechanical behavior of the material. The work of Birnbaum and Sofronis [6] proposes a hydrogen shielding mechanism that reduces the repulsive force between dislocations. The experimental results of Tabata and Birnbaum [7] confirm hydrogen elevates the velocity of dislocations in iron. In the hydrogen-enhanced, localized plasticity (HELP) model [6], the increased dislocation mobility in the presence of hydrogen generates a reduction of the local yield stress, leading to accelerated void growth ahead of the crack tip. The computational studies, found in Sofronis *et. al.* [8], show that a constitutive response based on the HELP model produces shear localization in metals. The reduction of local flow stress induced by hydrogen in a homogeneous material with properties characteristic of niobium influences significantly ductile void growth ahead of a stationary crack, as determined by Liang *et. al.* [9]. Ahn *et. al.* [10] predict a significant reduction of the crack growth resistance due to the effect of hydrogen in the earliest stages of growth as the crack tip emerges from the blunted tip. The steady-state fracture toughness of a propagating crack decreases in the presence of hydrogen, as shown in Sobotka *et. al.* [11].

In the present study, we extend the steady-state results of Sobotka *et. al.* to crack propagation in steel welds. The next section presents a brief overview of the concepts underlying the steady-state algorithm, the hydrogen enhanced plasticity model, and the computational implementation. Section 3 examines the effect on the active yield zone in mismatched welds, and Section 4 explores the impact on the hydrogen concentration due to the degree of material mismatch and to the level of the far-field applied constraint (characterized by the *T*-stress). A simple measure of void growth describes the influence of weld mismatch and far-field constraint in Section 5. The final section summarizes the results of the study and the major conclusions.

2. Modeling aspects

We consider a crack advancing at a constant velocity, $\dot{a}$, in the positive direction X_1 along the ligament at $X_2 = 0$. The near-tip fields exhibit invariance with respect to the crack tip in a sufficiently large domain beyond the site of crack initiation. The rate of change of a quantity, $\bullet$, with respect to time, t, depends on the distance from a point in the material to the crack tip by:

$$\partial(\bullet)/\partial t = -\dot{a}\,\partial(\bullet)/\partial X_1 \,. \tag{1}$$

Thus, rate-dependent equations, *e.g.* the constitutive relations, evolve along lines parallel to the X_1 axis, *i.e.* streamlines, and opposite to the direction of crack propagation. The integration of such equations along streamlines determines, without a time step integrator, the equilibrium values of the stress and inelastic strains. Equation (1) also implies that material properties, such as the initial yield stress, may not vary with respect to X_1, but may vary with respect to X_2. Cracks propagating at quasi-static rates generate negligible inertial forces. Varias and Shih [4] present further details of the formulation and the solution procedure.

Hydrogen exists at lattice or trap sties in metals, *e.g.* A533B pressure vessel steel, according to the theory of Oriani [12], and influences the material response in the elastic and plastic regimes under mechanical load, as in Sofronis *et. al.* [8]. The hydrogen at lattice sites in terms of hydrogen atoms per host metal atoms (H/M), c_L , and the mean stress, σ_m , follow the relationship:

$$c_L = \alpha\left(\beta - c_L\right)\exp\left(\gamma\,\sigma_m\right). \tag{2}$$

The parameters α , β , and γ signify constant material parameters for a steel at a temperature of $300\,K$ with an initial concentration of hydrogen at lattice sites, $c_L^0 = 2.4634\times10^{-8}\,H/M$. The amount of hydrogen at trap sites in H/M , c_T , grows with the plastic strains and c_L . The total concentration of hydrogen, $c = c_L + c_T$, decreases the barriers for dislocation movement and leads to a function of the local yield stress, σ_Y , of the form:

$$f\left(\sigma_Y, \sigma_0, c, \bar{\varepsilon}^p\right) = 0\,. \tag{3}$$

In Eqn. (3), the local yield stress decreases linearly with increasing values of c and rises according to a power law relationship with $\bar{\varepsilon}^p$; the value of σ_0 denotes the yield stress of the material without hydrogen. For all analyses in the present study, the specified value of c_L^0 produces a one percent reduction of σ_Y . Ahn *et. al.* [10] and Taha and Sofronis [13] present values of the material properties for A533B in the presence of hydrogen. The studies of Sofronis [14], Sofronis *et. al.* [8], and the WARP3D manual [15] provide the theoretical background and computational implementation of the constitutive response.

The crack advances along the center of a weld with $25\,\text{mm}$ height ($X_2 = \pm12.5\,\text{mm}$) in a modified small-scale yield model symmetric about the $X_2 = 0$ plane, illustrated in Fig. 1. The boundaries of the rectangular domain of finite elements, composed of 180,000 crossed, constant strain triangular elements, extend to $X_1 \times X_2 = 4000\times2000\left(J/\sigma_0^b\right)$, with the weld-base interface at $X_2/\left(J/\sigma_0^b\right) = \pm50$, for a remotely applied $K_I = 150\,\text{MPa}\sqrt{\text{m}}$ and the yield stress of the base material without hydrogen, $\sigma_0^b = 400\,\text{MPa}$. The displacements applied to the far-field boundaries follow the first two terms of the Williams' solution, K_I and the *T*-stress. The steel welds and base plate follow the same elastic-plastic constitutive model, but the yield stress of the steel weld without hydrogen, σ_0^w, varies to represent mismatched and generate material constraint effects.

3. Active plastic yielding region of a hydrogen charged material in a weld

Figure 1 displays the zone of active plastic yielding ahead of a crack tip located at $X_1 = 0$ for (a) matched, (b) 50% over-matched, and (c) 50% under-matched welds. The applied constraint, quantified by the *T*-stress, equals zero for all plots in Fig. 1. A positive *T*-stress restricts slightly the size of the active yield zone and increases yielding behind the crack tip. A negative *T*-stress promotes the growth of the active yield zone above and ahead of the crack tip.

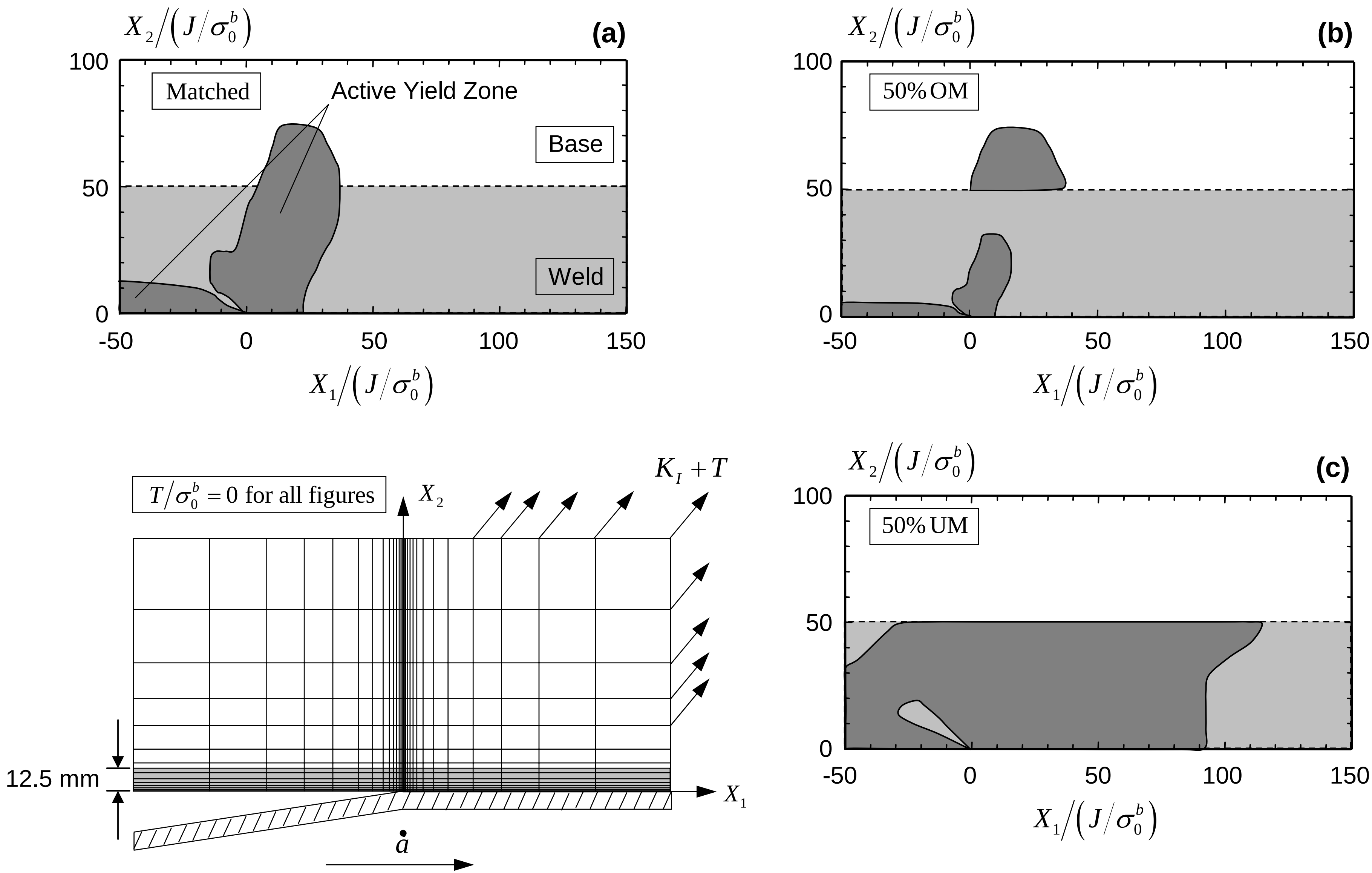

Fig. 1. Active zone of plastic yielding ahead of a steadily growing crack in a ductile weld with yield strength that is (a) matched, (b) over-matched, and (c) under-matched compared to the yield strength of the base metal.

The degree of weld-base mismatch affects significantly both the size and shape of the active yielding region. For a matched weld, shown in Fig. 1 (a), the advancing crack tip develops a continuous, active yield zone that extends to $X_1 \big/ \left(J/\sigma_0^b \right) = 20$ along the uncracked ligament. The size and profile of this active yield zone agree with the hydrogen free results of Varias and Shih [4]; the presence of hydrogen slightly extends the plastic zone boundaries. Within a weld over-matched by 50%, *e.g.* Fig. 1 (b), the size of the active yield zone decreases by roughly a factor of two, but within the base metal, the size of the active yield zone remains similar to the matched weld case. Between $35 \le X_2 \big/ \left(J/\sigma_0^b \right) \le 50$, the weld metal constrains the plastic zone within unyielded material and separates the active yield regions of the weld and base metal. Figure 1 (c) presents the active yield zone of a steadily propagating crack through a 50% under-matched weld. The active yield zone expands to $X_1 \big/ \left(J/\sigma_0^b \right) = 90$ along the uncracked ligament and terminates at the boundary between the weld and base metal. The higher yield strength of the base metal limits plastic yielding to the weld metal and prevents formation of the steady-state profile of the active yield zone shown in the matched and over-match welds. A pronounced trailing elastic sector develops behind the crack tip, as in previous studies without hydrogen [3].

4. *Effect of mismatch and constraint on hydrogen concentration*

Figure 2 displays the concentration of hydrogen under loading scaled by the initial concentration, c/c_L^0, along the uncracked ligament. The ratio c/c_L^0 varies with distance from the crack tip, the degree of mismatch, and the level of remote constraint, characterized by T/σ_0^b. The hydrogen present ahead of the crack tip influences strongly the deviatoric stresses, plastic strains, and mean stress.

The level of mismatch between the weld and base metal influences strongly the total concentration of hydrogen ahead of a propagating crack. Figure 2 demonstrates the highest ratios of c/c_L^0 develop in (b) over-matched followed by the (a) matched then (c) under-matched welds, *i.e.* the ratio of c/c_L^0 increases with the degree of mismatch. The mismatch ratio determines largely the hydrogen concentration ahead of a steadily propagating crack regardless of the *T*-stress. By implication, over-matched welds develop larger values of hydrostatic stress than under-matched welds, in the presence of hydrogen, but lower plastic strains.

Figure 2 shows that the *T*-stress influences marginally the hydrogen concentration, with the greatest effect in the under-matched weld. In matched and over-matched welds, the hydrogen concentration decreases slightly with the application of a non-zero *T*-stress. In under-matched welds, a positive *T*-stress reduces the hydrogen concentration, but a negative *T*-stress increases slightly the concentration of hydrogen and implies a higher mean stress, contrary to previous results for a steadily growing crack.

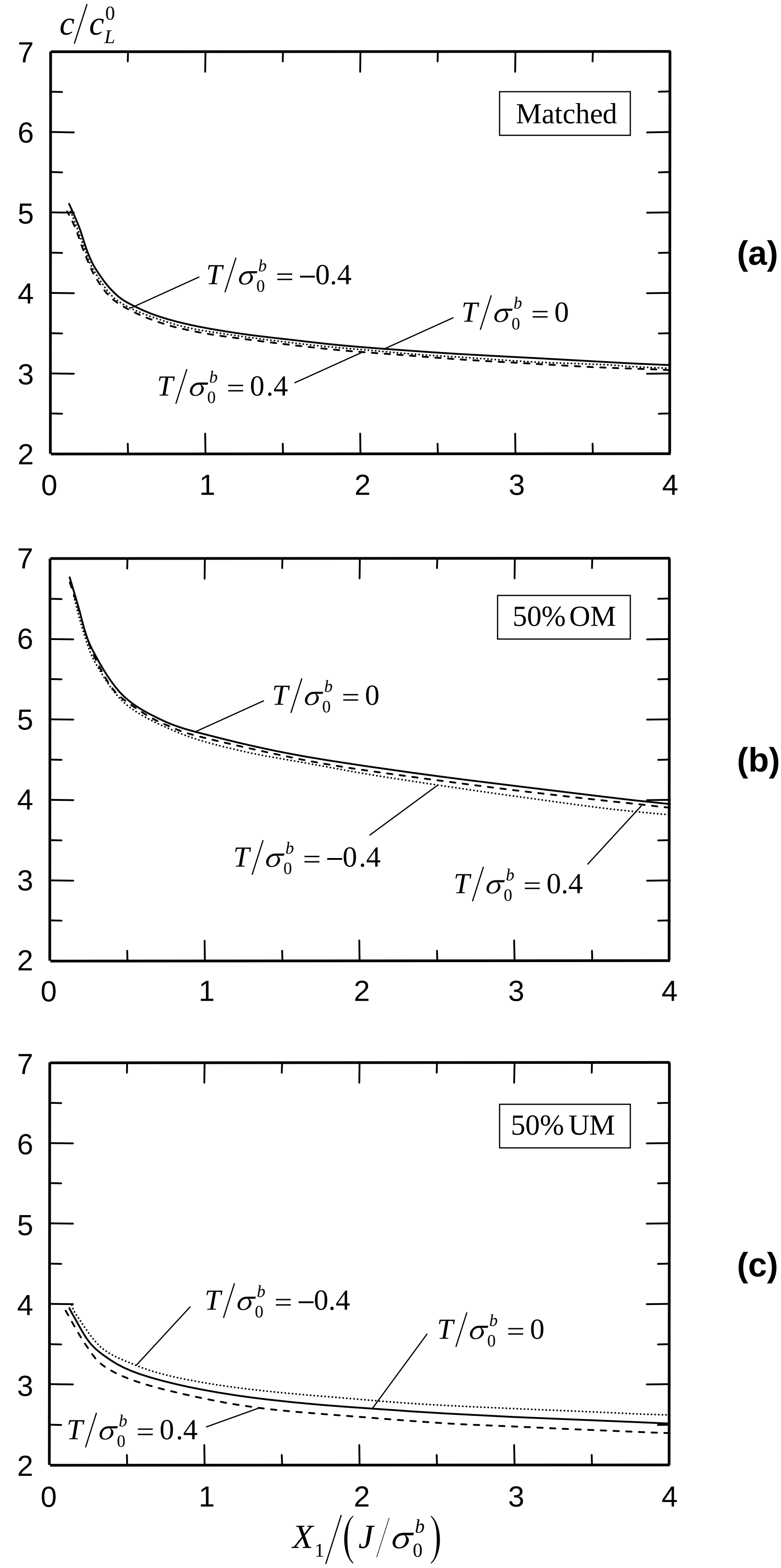

Fig. 2. Total hydrogen concentration, scaled by the initial concentration of hydrogen, along the uncracked ligament, ahead of a steadily growing crack in a ductile weld with yield strength that is (a) matched, (b) over-matched, and (c) under-matched compared to the yield strength of the base metal.

5. *Effect of weld mismatch and constraint on void growth*

The model of Rice and Tracey [16] provides a simple estimate of the void growth in a material. Let ζ denote $\ln(\rho/\rho_0)$, where ρ represents the current void radius and ρ_0 the original void radius. Then,

$$\zeta(X_1) = \int_{X_{1-R}}^{X_1} B \frac{\partial \bar{\varepsilon}^p}{\partial \lambda} \exp\left(\frac{3\sigma_m}{2\sigma_e}\right) d\lambda \,. \tag{4}$$

In Eqn. (4): B is a constant; and σ_e signifies the Von Mises stress. The integration in Eqn. (4) occurs along streamlines starting at the rightmost boundary (X_{1-R}) to the point X_1. The value of ζ increases monotonically on approach to the crack tip along the uncracked ligament. The reference void growth, ζ_{ref}, describes the void growth produced in a matched weld under a remote constraint of $T/\sigma_0 = 0$ in the presence of hydrogen. Figure 3 presents the normalized values of void growth along the uncracked ligament. The extent of weld to base strength mismatch, and to a lesser degree the level of applied *T*-stress, influences the magnitude of the void growth parameter. Hydrogen elevates the void growth parameter ahead of the uncracked ligament, irrespective of the degree of mismatch.

Hydrogen influences the mean stress, Von Mises stress, and plastic strain and, thus, generates competing effects in values of the void growth parameter, ζ. Detailed evaluation of these quantities along the uncracked ligament reveals that differences in the plastic strain, $\bar{\varepsilon}^p$, due to strength mismatch generate the majority of variations in values of ζ. The triaxiality parameter, $3\sigma_m/2\sigma_e$, varies marginally for these combinations of strength mismatch and *T*-stress, and does not exceed $\pm5\%$ of the value in a matched weld with $T/\sigma_0 = 0$ over distances $0 \le X_1/(J/\sigma_0) \le 4$.

Figure 3 (a) displays the void growth in a matched weld for the applied constraint levels of $T/\sigma_0^b = 0, \pm 0.4$. The ratio ζ/ζ_{ref} remains largely constant with respect to distance ahead of the crack tip. Non-zero values of the *T*-stress reduce the magnitude of void growth by suppressing plastic strain, and configurations under high constraint produce less plastic strain than configurations under low constraint. In Fig. 3 (b), values of the void growth parameter decline in an over-matched weld compared to a matched weld, again largely due to the reduction in plastic strain. Non-zero values of the *T*-stress further reduce void growth, but in over-matched welds, negative *T*-stress prevents void growth more effectively than positive *T*-stress.

Under-matched welds promote the development of significant void growth, as shown in Fig. 3 (c), through a substantial increase of plastic strain. These high values of ζ/ζ_{ref} imply substantial damage to the material prior to approach of the advancing crack and suggest a lower $J-\Delta a$ curve. The magnitude of void growth in an under-matched weld exceeds the magnitudes of void growth in the matched and over-matched welds. Furthermore, the application of a negative *T*-stress leads

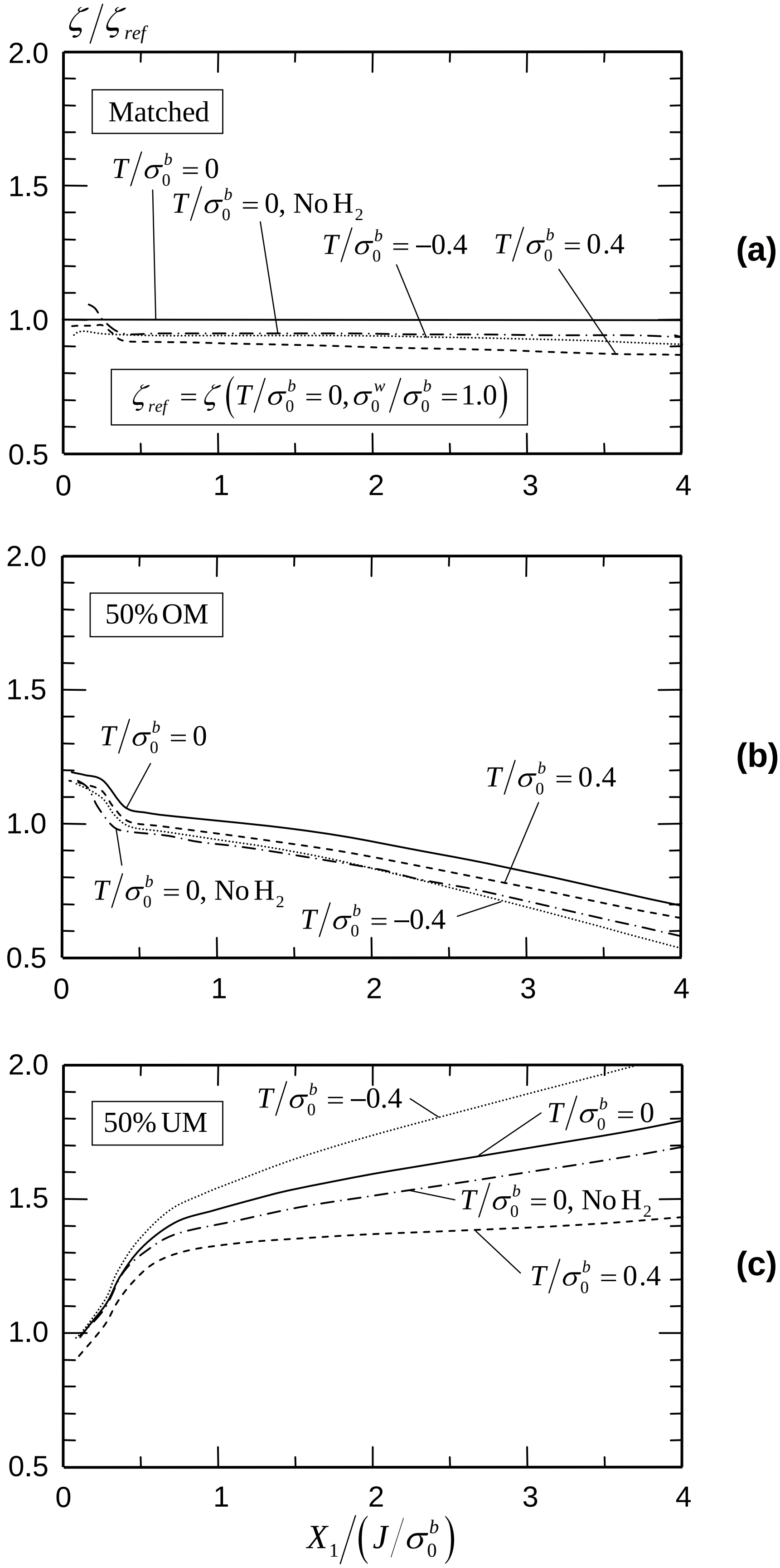

Fig. 3. Void growth parameter scaled by the reference void growth parameter at the same point along the uncracked ligament, ahead of a steadily growing crack in a ductile weld with yield strength that is (a) matched, (b) over-matched, and (c) under-matched compared to the yield strength of the base metal.

to void growth above values found in the zero *T*-stress configuration and generates the largest void growth values found in the present study.

6. Summary and Conclusions

The present study examines the near-tip fields of a steadily growing crack in mismatched steel welds in the presence of hydrogen for the Stage II regime of sustained load crack growth. A constitutive relation, based on the hydrogen-enhanced localized plasticity (HELP) mechanism, describes the effect of hydrogen through changes in the local flow stress. Constraint effects due to the degree of weld mismatch and to the remotely applied loading (*T*-stress) generate substantial changes in the shape and size of the active yielding region, the hydrogen concentration, and the void growth.

Weld metal-base metal mismatch of the yield stress leads to extensive changes in the near-tip fields. The region of active yielding shrinks in over-matched welds and expands in under-matched welds. The mean stress, and consequently the hydrogen concentration, in a weld increase with increasing levels of over-match, but the reduction in plastic strain due to the over-match diminishes the effects of increased triaxiality, thereby leading to a net decrease in comparable void growth. Void growth increases significantly for under-matched conditions due to increased plasticity and suggests that the steady-state fracture toughness of an under-matched weld may be significantly lower than a matched or over-matched weld.

The relative impact of remotely applied, far-field constraint, characterized by the *T*-stress, depends on the mismatch of the weld. The *T*-stress – positive or negative – generates a minimal reduction of the pointwise values of hydrogen concentration, c/c_L^0, in matched and over-matched welds; in under-matched welds, this ratio increases with a negative *T*-stress and decreases with a positive value of the *T*-stress. The *T*-stress influences marginally the void growth in matched and over-matched welds in this material, A533B. In under-matched welds, the void growth depends strongly on the level of *T*-stress. Positive *T*-stress values suppress void growth, but negative *T*-stress values accelerate void growth, producing the highest void growth for steadily propagating crack found in this study.

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