QUANTITATIVE EVALUATION OF HYDROGEN INDUCED COLD CRACKING IN WELDED JOINTS

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Abstract

The hydrogen assisted cracking in viewpoint of fracture mechanics is described. After characteristic the actual conditions of the cold cracking in weld joints shows the possibilities of used the threshold stress intensity factor K_{Ith} to evaluate the fracture resistance of material. There was established a modified Oriani- van Leeuwen relation and determined the normalised parameter $k_{nor} = K_{Ith} / K_{IC}$. In this solution is considered the influence of the constraint effect in mismatched weld joints on cold cracking resistance.

Introduction

Hydrogen facilitate the cracking of steels. The cracks are a most detrimental of all discontinuities in weldments. One of the significant aspect of high strength steel weldability is the hazard of hydrogen induced cracking during or after welding and functioning of welded constructions. Generally cracks could be formed either during welding i.e., soon after solidification, which is hot cracking, on after the bead has cooled to room temperature which is cold cracking. The cold cracking occurs when the condition outlined below comes simultaneously:

- hydrogen is present to a sufficient degree,
- tensile stresses act on the weld which are a result of the weld thermal cycle,
- a susceptible weld metal or heat affected zone microstructure is present which is expressed by fracture toughness.

These factors interact in a complex manner so that quantitative treatment of the subject is extremely difficult.

From physical point of view this process is interpreted by action of some factors such as [1, 2]:

- pressure of molecular hydrogen in microvoids of metal,
- a decrease of interatom bonds in metal under the influence of dissolved hydrogen,
- hydrogen will reduce the effective surface energy of the crack and under such condition the crack can propagate at lower nominal stress than hydrogen - free specimens,
- hydrogen interferes with dislocations in a manner which facilitates different types of fracture, including microvoid coalescence, quasicleavage fracture and intergranular fracture.

Presently a lot of hypotheses of hydrogen embitterment have been proposed to explain the origin of this phenomenon. But the principal demerit of theirs is a consideration of only a some part of so complicated process as cold cracking.

1. Hydrogen assisted cracking in viewpoint of fracture mechanics

Hydrogen embrittlement as a problem is mainly associated with ferritic steels [2, 3]. It is well know that the tendency for hydrogen – induced cracking increases as the yield strength of the steel is increased. The hydrogen tends to collect at regions of stress concentration.

Presently models for assess of the hydrogen assisted cracking are based on the mathematically – physical approaches and are predominantly base on calculation of crack initiation and propagation [4].

Crack models preferentially based on the influences of the mechanical load and might be approaches considering mainly:

- local stress and strain,
- fracture mechanics parameters and criterions.

For instance, a general formula to evaluate the hydrogen dependent stresses σ_{crit} in any materials is developed [5]:

$$\sigma_{crit} = \sigma_o - \alpha \, log\left(\frac{C}{C_x}\right) \tag{1}$$

where:

σ_o - crack critical stress without hydrogen,
α - material constant,
C - local hydrogen concentration,
C_x - hydrogen concentration without effect on the critical stress.

The mathematical expression to describe the critical fracture strain ε_{crit} is [6]:

$$\varepsilon_{crit} = \varepsilon_o - A' \cdot C \tag{2}$$

where:

C - local hydrogen concentration,
A' - material dependent constant,
ε_o - material dependent constant.

The concentrations of hydrogen at a region of elevated stress can be estimated by means of the thermodynamic relation [7]:

$$C = C_o \, exp\left(\sigma_H \overline{V} / RT\right) \tag{3}$$

where $\overline{V}$ is the molar volume of hydrogen in iron, and $\sigma_H = \left(\sigma_{11} + \sigma_{22} + \sigma_{33}\right)/3$ is the hydrostatic tensile stress. The maximum value of σ_H ahead of crack can be estimated as about three times the yield stress for perfectly plastic materials [7]. C_o is the hydrogen concentration in equilibrum with hydrogen at pressure p in the absence of stress and is given by:

$$C_o = 0.00185 \, p^{1/2} \, exp\left(-Q/RT\right) \tag{4}$$

where Q is the heat of solution of hydrogen in iron, 28.6 kJmol^{-1}.

If we will be based on the fracture mechanics a useful formula for evaluation of the

critical stress intensity factor K_{crit} from the stress $\sigma_{erf}(C)$ required for crack propagation at a specific hydrogen concentration is established by Oriani [8]:

$$K_{crit} \geq \sigma_{erf}(C) \cdot \sqrt{\alpha \cdot \pi \cdot c} \tag{5}$$

where
:

c - crack length,
α - constant for specimen and crack geometry.

Fracture mechanics (FM) is presently used to determine local stresses and strains. Furthermore FM is also directly incorporated into models for hydrogen assisted cracking such as cold cracking. In those models linear elastic fracture mechanics in terms of a stress intensity factor K for static loading is predominantly applied [4].The local hydrogen concentration C is determined by analytical and numerical methods. The value of C is then compared with a critical hydrogen concentration C_{crit} which is dependant on the actual mechanical load.

The local microstructure is predefined and is considered implicitly in modelling by crack criteria which are based on the critical and hydrogen dependent material properties.

More advances model then reported by eq. (5) of process of hydrogen assisted cracking is the Oriani-van Leeuwen conception which base on the normalised fracture parameter K_{Ith} which become adapted by Lancaster to welded joints [9]. This model is the basis to further consideration in this paper.

2. Quantitative evaluation of the hydrogen induced cold cracking in welded joints

Presented solutions in [9, 10] are executed at foundation that material owns isotropic physical properties. The normal way to calculate the strength of multiphase alloy is use a rule of mixtures, i.e. to estimate a mean value from the weighted average of each component [10]:

$$\sigma = \sum_{i=1}^{n} \sigma_{\alpha} V_{\alpha} + \sigma_B V_B + ... + \sigma_i V_i \tag{6}$$

$$\sum_{i=1}^{n} V_i = 1 \tag{7}$$

where:

σ_i - the property assigned to phase i,
V_i - volume fraction of phase i.

Above approximation may be not valid in circumstances where the phase have very different mechanical properties. This take place because of constraint effect between different components of structure. For example the characteristic of strength of constrained bainite in martensite matrix is established as follows [10]:

$$\sigma_b \cong \sigma_{bo}\left[0,65exp\left(-3,3V_b\right)+0,98\right] \leq \sigma_M \tag{8}$$

where:

σ_b - strength of the constrained bainite,

σ_{bo} - strength of the unconstrained bainite,

V_b - volume fraction of the bainite,

σ_M - strength of the martensite.

When the volume fraction V_b of bainite is small, its strength nearly matches that of martensite.

In accordance with above established rules the constraint effects are important in determining the mechanical behaviour of weld metal and heat effected zones (HAZ) microstructures in many respects. For example, it was indicated that hard-phase islands present in HAZ microstructures are most detrimental when they are severely constrained by the surrounding microstructure. It can lead to significant variations in measured fracture toughness values of the same material.

Then concern must be given to the constraint effect on deformation behaviour, especially in the non-linear region of behaviour.

In order to solve this problem for mismatched welded joints, the simplified model is create with thin layer W (soft or hard – representing the weld metal) and it is presented in Fig.1.
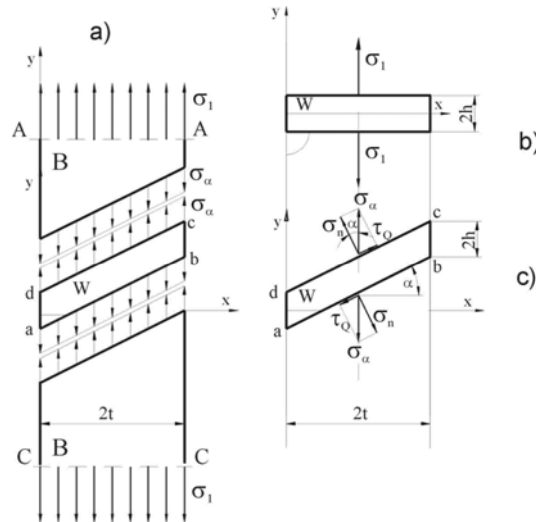

FIGURE1. Characteristic of the model of mismatched weld joints: (a) geometrical configuration - layer W is inclined to external load and distribution of external stresses σ_1 and σ_α; (b) external stress at interface for perpendicular layer; (c) external stress at interface for inclined layer.

The constraint effect is causes that the yield strength σ_{ys} is increased or decreased and is depending on constraint factors K_W^{un}, K_W^{ov} for under- and overmatched weld joints respectively and in accordance to [11] is determined as:

$$\sigma_{ys}^{un} = \sigma_{ys}^{W} K_W^{un} \tag{9}$$

$$\sigma_{ys}^{ov} = \sigma_{ys}^{W} K_W^{ov} \tag{10}$$

Finally, we received the relation K_{Ith} / K_{IC} as follows [11]:

- undermatched weld joints

$$k_{norm} = \frac{K_{Ith}}{K_{IC}} = \frac{1}{1 + \left(\frac{p}{p_0}\right)^{\frac{\gamma}{2}} \left[b\left(\sigma_{ys} \cdot K_W^{un}\right)^{\frac{1}{2}}\right]^{-1} exp\left[A\left(\sigma_{ys} \cdot K_W^{un}\right)^{\frac{1}{2}} - B\left(\sigma_{ys} \cdot K_W^{un}\right)\right]}$$

(11)

- overmatched weld joints

$$k_{norm} = \frac{K_{Ith}}{K_{IC}} = \frac{1}{1 + \left(\frac{p}{p_0}\right)^{\frac{\gamma}{2}} \left[b\left(\sigma_{ys} \cdot K_W^{ov}\right)^{\frac{1}{2}}\right]^{-1} exp\left[A\left(\sigma_{ys} \cdot K_W^{ov}\right)^{\frac{1}{2}} - B\left(\sigma_{ys} \cdot K_W^{ov}\right)\right]}$$

(12)

$$A = \frac{2(1+v)\overline{V}}{3RT}\left(\frac{2E}{\pi}\right)^{1/2} \quad ; \quad \left(MNm^{-2}\right)^{1/2}$$

(13)

$$B = \frac{2(1+v)\overline{V}}{RT}\left(\frac{2}{\pi}\right) \quad ; \quad \left(MNm^{-2}\right)^{-1}$$

(14)

$$b = \frac{2}{\beta}\left(\frac{2E}{\pi}\right)^{1/2} \quad ; \quad \left(MNm^{-2}\right)^{-1}$$

(15)

where:

E - modulus of elasticity, MNm^2,
v - Poisson's ratio,
R - gas constant, 8.134 J $mol^{-1}K^{-1}$,
T - temperature, K,
$\overline{V}$ - partial molar volume of hydrogen in iron, m^3 mol^{-1},
σ_{ys} - yield strength, MPa,
K_{Ith} - threshold value of the stress intensity factor for initiating subcritical hydrogen - assisted crack growth, MPa $m^{1/2}$,
K_{IC} - critical stress intensity factor without hydrogen, MPa $m^{1/2}$,
p/p_o - hydrogen pressure in atmospheres,
β, γ - constants,
K_W^{un}, K_W^{ov} - constraint factors.

The constraint factors K_W^{un}, K_W^{ov} for under- and overmatched weld joints in accordance to ref. [12] yields:

$$K_W^{un} = \frac{2}{\sqrt{3}}\left[\frac{1}{4(1-q)}\left[\frac{\pi}{2} + 2(1-2q)\sqrt{q(1-q)} - arc\,sin(2q-1)\right] + (1-q)\frac{1}{4\kappa}\right] \quad (16)$$

$$K_W^{ov} = \frac{2}{\sqrt{3}}\left[\frac{1}{4(1-q)}\left[-\frac{\pi}{2} - 2(1-2q)\sqrt{q(1-q)} - arc\,sin(2q-1)\right] + (1-q)\frac{1}{4\kappa}\right] \quad (17)$$

where

:

κ -   relative thickness of soft or hard zone, ($\kappa = 2h / 2t$ – Fig. 1),

q   -   parameter, $0 \leq q < 1$.

For example some values of $K_W^{un/ov}$ are presented in Table 1.

TABLE 1. Some values of constraint factor $K_W^{un/ov}$.

No	q	$\chi = 2h/2t$					
		0,05	0,10	0,20	0,30	0,40	0,50
		overmatching case					
1	0	5,7740	2,8870	1,4430	0,9623	0,7217	0,5774
2	0,1	4,8360	2,2380	0,9387	0,5057	0,2892	0,1593
		undermatching case					
3	0	6,6800	3,7940	2,3500	1,8690	1,6290	1,4840
4	0,1	6,1510	3,5530	2,2540	1,8210	1,6050	1,4750

The parameter q represents the external normalised tangential stress at interfaces between zones W and B and is established as follows:

$$q = \frac{\sigma_1}{k} \sin 2\alpha \qquad (18)$$

where:

σ_1 -   external stress – Fig. 1,

k   - $\sigma_{ys} / \sqrt{3}$,

α -   angle of inclined layer – Fig.1.

According to equations (16), (17) we will define boundary value of κ when constraint factor owns condition $K_W^{un/ov} \geq 0$. After transformation eq. (16), (17) we will receive κ_{lim} as a function of q:

- undermatched weld joints

$$\kappa_{lim} = \frac{-\left(-2 + 4q - 2q^2\right)}{\left[-\pi - 4\sqrt{q}\sqrt{1-q} + 8q^{\frac{3}{2}} \cdot \sqrt{1-q} + 2\,arc\,sin\left(2q-1\right)\right]} \qquad (19)$$

- overmatched weld joints

$$\kappa_{lim} = \frac{-\left(-2 + 4q - 2q^2\right)}{\left[\pi + 4\sqrt{q}\sqrt{1-q} - 8q^{\frac{3}{2}} \cdot \sqrt{1-q} + 2\,arc\,sin\left(2q-1\right)\right]} \qquad (20)$$

q = 0,01, 0,02,…,0,99.

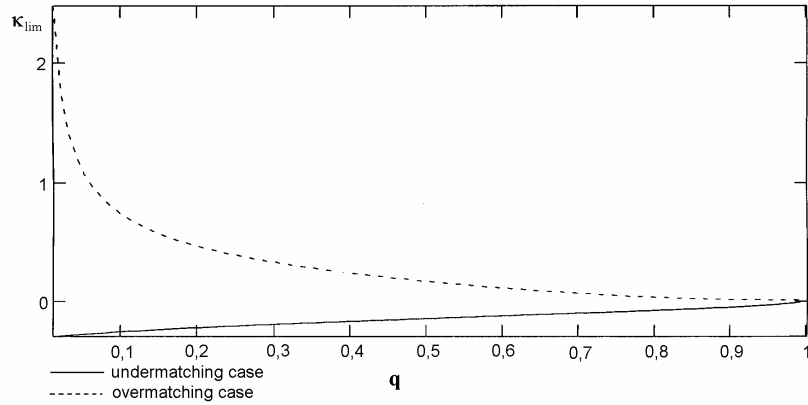The results of calculations are presented in Fig. 2.

FIGURE. 2. Limited values of κ_{lim} in agreement with eq. (19), (20).

The established normalised parameter $k_{norm} = K_{Ith} / K_{IC}$ in agreement with eq. (11), (12) is considered generally the influence of constraint effect in mismatched welded joints on cold cracking resistance. When k_{norm} is less then 1 it indicate on the step of susceptibility of welded joints on hydrogen cold cracking.

For example we will use above solution to calculate the susceptibility of low alloy steel 14HNMBCu on hydrogen cold cracking. The date to calculation for this steel are as follows:

$$A = 6.926 \cdot 10^{-5} \, (N/m^2)^{-1/2} \,, \quad b = 4.7895 \cdot 10^{-5} \, (N/m^2)^{-1/2} \,,$$
$$B = 3.242 \cdot 10^{-10} \, (N/m^2)^{-1} \,, \quad \gamma = 0.26375 \,, \qquad \sigma_{ys} = 9.038 \cdot 10^{8} \, (N/m^2)$$

Besides, according to Lancaster [13] we can substitute formulation $(p / p_o)^{\gamma / 2}$ in eq. (9), (10) by $(C / C_o)^{\gamma} = (5,18 \, C)^{0,26375}$, where C it means the degree of concentration of hydrogen in metal. Some values of normalised parameters of k_{norm} (C, K_W) presented in Table 2.

TABLE 2. Values of k_{norm} (C, K_W) for low alloy steel 14HNMBCu.

Lp.	C cm³/100g	K_W -	k_{norm} -	C cm³/100g	K_W -	k_{norm} -	C cm³/100g	K_W -	k_{norm} -
$K_W \geq 1$									
1.	$5 \cdot 10^{-4}$	1	0.537	$5 \cdot 10^{-4}$	2	0.481	$5 \cdot 10^{-4}$	3	0.44
2.	$5 \cdot 10^{-2}$	1	0.256	$5 \cdot 10^{-2}$	2	0.216	$5 \cdot 10^{-2}$	3	0.189
3.	1.00	1	0,135	1.00	2	0.111	1.00	3	0.096
4.	5.00	1	0,093	5.00	2	0.075	5.00	3	0.065
5.	10.00	1	0,078	10.00	2	0.064	10.00	3	0.054
$K_W \leq 1$									
6.	$5 \cdot 10^{-4}$	0,25	0.568	$5 \cdot 10^{-4}$	0.50	0.565	$5 \cdot 10^{-4}$	0.85	0.546
7.	$5 \cdot 10^{-2}$	0,25	0.281	$5 \cdot 10^{-2}$	0.50	0.279	$5 \cdot 10^{-2}$	0.85	0.263
8.	1.00	0,25	0.151	1.00	0.50	0.149	1.00	0.85	0.139
9.	5.00	0,25	0.104	5.00	0.50	0.103	5.00	0.85	0.096
10.	10.00	0,25	0.088	10.00	0.50	0.087	10.00	0.85	0.081

The results of this study of mismatched weld joints reveals dependence of normalised parameter $k_{norm} = K_{Ith} / K_{IC}$ on the constraint factor K_W at different hydrogen concentration C.

It belongs to ascertain that according to [1] the noticeable change of plasticity of low alloy steels take place even at low concentration of diffusible hydrogen as few $3 \cdot 10^{-1}$ cm^3 / 100 g. There is equivalent with simultaneous drop of material fracture resistance. Experimental research of similar kind of steels as low alloy steel 14HNMBCu indicate on the high step of susceptibility of welded joints on hydrogen cold cracking even at C = $(5 - 8) \cdot 10^{-1}$ cm^3 / 100 g where the relation K_{Ith} / K_{IC} is equal from 0.5 to 0.12 [14].

In above presented data the value of C means the concentration of diffusible hydrogen. Structural defects such as dislocations, voids, non-metallic inclusion, interphase and intergrain boundaries are able to accumulate of vastly more hydrogen content than regular lattice sites. The transport of hydrogen to site of its locale action plays a decisive role in embrittlement due to hydrogen.

In accordingly with fracture mechanics we can assuming that cracking take place at crack tip then the yield strength locally is raised by constraint at the root of the crack with simultaneous concentration of hydrogen. Beside very important role plays constraint caused by local change of microstructure in welded joints. These factors are taken into consideration in solutions determined by eq. (11), (12).

Presented solutions are appropriate to explain the philosophy of influence the constraint effect on the hydrogen cold cracking. These solutions have a universal form for under- and overmatched welded joints – Fig. 1 because that base on normalised parameters. If exist complex microstructure in different zones of welded joints there appear inconveniences and gets necessity to determination of mean yield strength for each zone.

If we know values of k_{norm} and K_{IC} for material we can also define directly parameter K_{Ith}: $K_{Ith} \rightarrow k_{norm} \cdot K_{IC}$. Then the subcritical hydrogen – assisted crack growth doesn't take place when:

$$K_I \leq K_{Ith} \tag{19}$$

where: K_I – stress intensity factor.

Conclusion

The theoretical analysis form a basic to an assessment of the relation $k_{norm} = K_{Ith}$ / K_{IC} for mismatched weld joints. There was established a modified Oriani – van Leeuwen equation by introduction to calculation the constraint factor $K_W^{un/ov}$. It enable the quantitative assessment of constraint effect in mismatched weld joints on cold cracking at different hydrogen concentration C.

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