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ANALYSIS OF THE HETEROGENEOUS WELD JOINTS IN ASPECT OF FRACTURE MECHANICS

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Abstract

This paper will discuss the issues relating to the effect of constraint on the fracture safe design. At first the attention is focused on the relation between the microstructure and selected mechanical properties. This aspect is illustrated with presenting a brief consideration of the constraint effect in relation: microstructure - mechanical properties in microscopic scale. The same problem is account in macroscopic scale of the heterogeneous weld joints. After formulating a simplified model of mismatched weld joints a concise review of stress was made at interfaces between zones (W) and (B). Conclusions from above analysis form a constraint parameters $K_R^{un/ov}$ *which were used to an assessment of the fracture parameters as ratio of driving forces* $\delta_R^{un/ov}$ *by modified of the classical solution presented by Engineering Treatment Model (E-T-M).*

Key words: *material microstructure, constraint effect, fracture parameters*

1. Introduction

The weld joints are often highly heterogeneous. It is known that a fracture of welded structures is generally caused by various defects in welded joints, while macro - mechanical heterogeneity is one their primary features. The heterogeneous nature of the weld joints are characterised by macroscopic dissimilarity in mechanical properties. This dissimilarity is caused by different mechanical and chemical properties of the weld and base materials as well as by the thermal and strain cycles during welding and may occur through the fusion line and heat affected zone (HAZ) of welds. The most reliable and practically feasible design concept is designing against fracture initiation from crack like defects in weldments. This design concept suggests that the fracture toughness of all parts of the welded joints must be went over and the lowest toughness region should be recognised. A weld joint includes the weld metal, HAZ and the base metal parts having different properties. Welding is probably the most popular manufacturing process for joining metals used in structural applications. In this situation we will focus our attention on a model in which the weld metal or part of the heat affected zone (HAZ) is imitated by layer (W) - Fig. 1c and d. Strength mismatching occurs as an overmatching - Fig. 1a or as an undermatching - Fig. 1c. The essential physical phenomena affecting the mechanical properties of this model occur at the interfaces of zones (B) and (W) - Fig. 1c and d. The presence of the interfaces in these models naturally gives rise to mechanical constraint on the weld joints. A fracture safe design also can be influenced by constraint. The analysis of failure in a structural component depends on two inputs, the fracture behaviour and deformation behaviour - both depend on constraint. Current work has concentrated more on looking at constraint effects on the fracture behaviour.

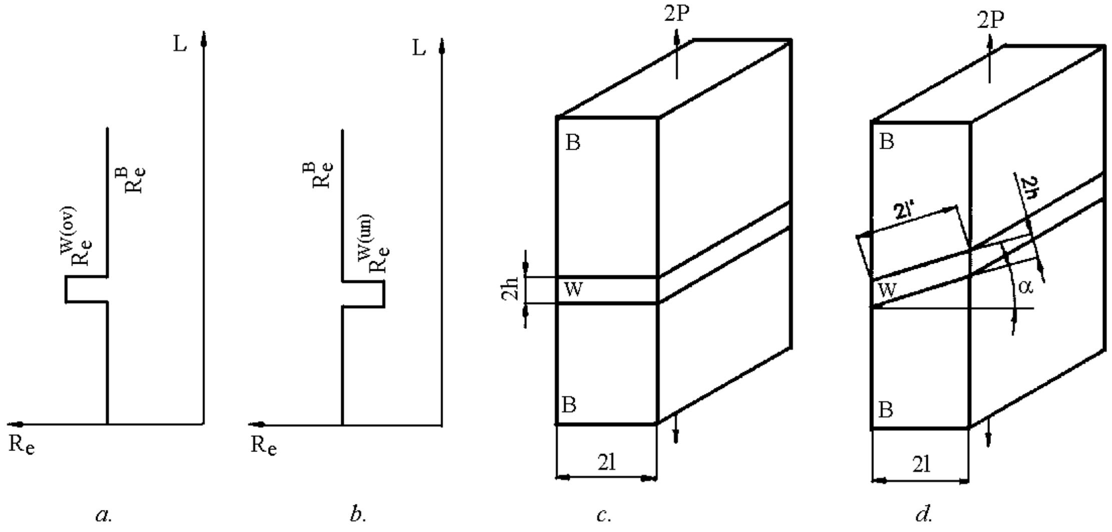

Fig.1. Characteristic of the models of the mismatched weld joints: (a) change of the yield point $R_e^{W(ov)}$ in the overmatched weld joint; (b) change of the yield point $R_e^{W(un)}$ in the undermatched weld joint; (c, d) geometrical configuration - layer W as perpendicular or incline to external load 2P.

2. Influence of the constraint effect on the material microstructure

The normal way to calculate the strength of a multiphase alloy is to use a rule of mixtures, i.e. to estimate a mean value from the weighted average of each component:

$$\sigma = V_\alpha \sigma_\alpha + V_b \sigma_B + V_p \sigma_p + V_M \sigma_M + V_\gamma \sigma_B + \ldots, \tag{1}$$

where:

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

Above approximation may not be valid in circumstances where the phases have very different mechanical properties. This take place because of constraint effect between different components of microstructure. For example on Fig. 2 is presented plots of normalised strength of bainite as the function of fraction of bainite in martensitic matrix and change of proof stress of bainite and martensite in mixed microstructure which has been tempered.
Then the strength of constrained bainite is established as follows [1]:

$$\sigma_b \cong \sigma_{bo}\left[0{,}65\, exp(-3{,}3V_b) + 0{,}98\right] \le \sigma_M\, , \tag{2}$$

where:
σ_b - strength of constrained the bainite,
σ_{bo} - strength of unconstrained the bainite,

V_b	-	volume fraction of bainite,
σ_M	-	strength of the martensite.

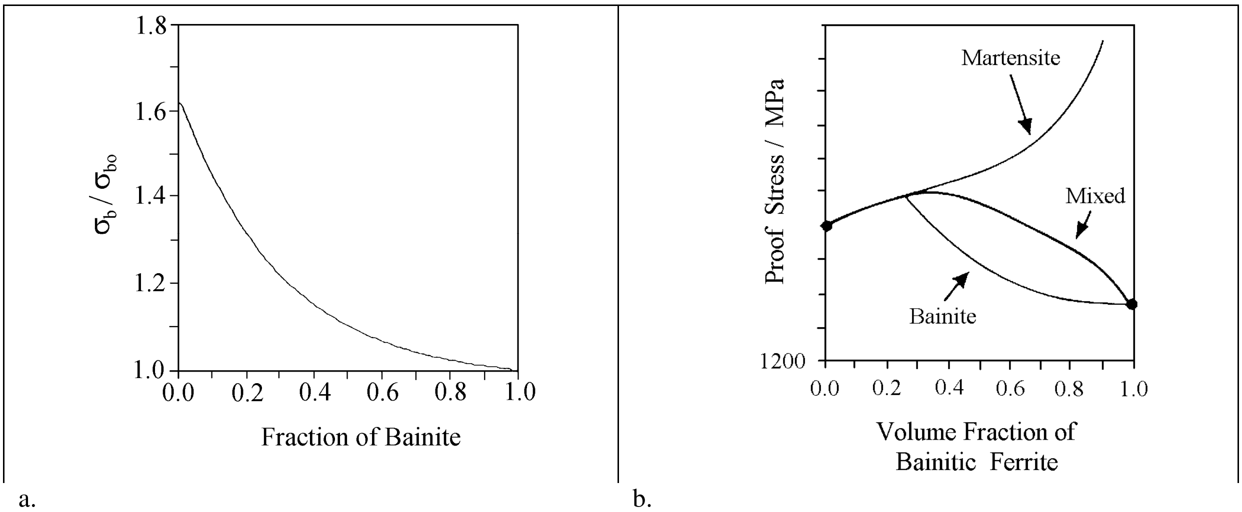

Fig. 2. Characteristic of the strength of constrained bainite in martensite matrix [1]:
(a) the normalised strength of bainite as the fraction of bainite in martensitic matrix; (b) the strength contributions of bainite and martensite in the mixed microstructure which has been tempered.

When the volume fraction V_b of bainite is small, its strength nearly matches that of martensite - Fig. 2. In accordance with above established rules the constraint effect are important in determining the mechanical behaviour of weld and 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 was also noted that microstructural inhomogeneities such as hard pearlite island, can lead to a significant variations in measured fracture toughness values of the same material.

3. Influence of constraint effect on the fracture of heterogeneous weld joints - macroscopic scale

Determination of change in the state of stress occurring at the interface of zones (B) and (W) is than of primary importance for a correct interpretation and estimation of a new mechanical properties. The stress analysis in this area is made previously in [2]. A very useful form of the stress state we can received by change the parameters: $\gamma \rightarrow q$. The parameter γ represent the internal normalised tangential stress at interfaces and the parameter q is represent the external normalised tangential stress caused by force 2Q. With use the relation between γ and q as:

$$\gamma + 1 = 2q \rightarrow \gamma = 2q - 1, \qquad \text{(3a, b)}$$

we can transform the stress state which was established previously [2] on the form very useful in practice as follows:

- undermatching case:

$$\sigma^{un}_{xx(\,rel\,)} = \frac{\sigma^{un}_{xx}}{k} = \frac{1}{2(1-q)}\left[\left(\frac{\pi}{2} + 2(1-2q)\sqrt{q(1-q)} - arcsin(2q-1)\right)\right] + (1-q)\frac{\xi}{\kappa} - \qquad (4)$$

$$-2\sqrt{1-\left(q+(1-q)\frac{\eta}{\kappa}\right)^2}\ ,$$

$$\sigma^{un}_{yy(\,rel\,)}=\frac{\sigma^{un}_{yy}}{k}=\frac{1}{2(1-q)}\left[\frac{\pi}{2}+2(1-2q)\sqrt{q(1-q)}-arcsin(2q-1)\right]+(1-q)\frac{\xi}{\kappa}\,, \tag{5}$$

$$\sigma^{un}_{xy(\,rel\,)}=\frac{\sigma^{un}_{xy}}{k}=q+(1-q)\frac{\eta}{\kappa}\,, \tag{6}$$

$$q=\frac{\tau_Q}{k}\,,\ k=\frac{R_e^{W(un)}}{\sqrt{3}}\ ,\ R_e^{W(un)}\le R_e^B\ ,\ \tau_Q=\frac{Q}{A}$$

- overmatching case

$$\sigma^{ov}_{xx(\,rel\,)}=\frac{\sigma^{ov}_{xx}}{k}=-\left[\frac{1}{2(1-q)}\left[\left(\frac{\pi}{2}+2(1-2q)\sqrt{q(1-q)}-arcsin(2q-1)\right)\right]+(1-q)\frac{\xi}{\kappa}-\right.$$
$$\left.-2\sqrt{1-\left(q+(1-q)\frac{\eta}{\kappa}\right)^2}\ \right], \tag{7}$$

$$\sigma^{ov}_{yy(\,rel\,)}=\frac{\sigma^{ov}_{yy}}{k}=\frac{1}{2(1-q)}\left[-\frac{\pi}{2}-2(1-2q)\sqrt{q(1-q)}+arcsin(2q-1)\right]+(1-q)\frac{\xi}{\kappa}\,, \tag{8}$$

$$\sigma^{ov}_{xy(\,rel\,)}=\frac{\sigma^{ov}_{xy}}{k}=q+(1-q)\frac{\eta}{\kappa}\,, \tag{9}$$

$$q=\frac{\tau_Q}{k}\,,\ k=\frac{R_e^{W(ov)}}{\sqrt{3}}\ ,\ R_e^{W(ov)}>R_e^B\ ,\ \tau_Q=\frac{Q}{A}\,,\ \kappa=\frac{2h}{2t}\,;\ \eta=\frac{2y}{2t}\,;\ \xi=\frac{2x}{2t}\,;\ \kappa\ge\eta\,.$$

In practice, by used to consideration the external force 2P and inclined layer we can determining the value of external tangential stress acting at interface as follows:

$$\tau_Q=\frac{\sigma_1}{2}sin2\alpha\,, \tag{10}$$

where:

$\sigma_1 = 2P/A$		
2P	-	tensile force, Fig.1,
$A = 2\,t\cdot L$	-	cross - section perpendicular to 2P,
α	-	angle, Fig. 1.

Then it is possible to assess the value of q as:

$$q = \frac{\sigma_1}{2k} sin2\alpha , \tag{11}$$

The stress analysis to enables establish the quantitatively assessment of constraint effect by introduce the constraint factor for the under- and overmatched weld joints in accordance to references [3], as follows:

$$K_W^{un} = \frac{2}{\sqrt{3}}\left(\frac{1}{4(1-q)}\left[\frac{\pi}{2} + 2(1-2q)\sqrt{q(1-q)} - arcsin(2q-1)\right] + (1-q)\frac{1}{4\kappa}\right), \tag{12}$$

$$K_W^{ov} = \frac{2}{\sqrt{3}}\left(\frac{1}{4(1-q)}\left[-\frac{\pi}{2} - 2(1-2q)\sqrt{q(1-q)} + arcsin(2q-1)\right] + (1-q)\frac{1}{4\kappa}\right), \tag{13}$$

Fig. 3a, b presents the dependence of the constraint factors $K_W^{un/ov}$ on the parameters κ and q. Because of that the model is based on the assumption that the materials of zones B and W are ideal plasticity than the new value of yield point of the layer is equal:

- undermatching case $\left(R_e^W < R_e^B\right)$:

$$R_e^{W(un)} = K_W^{un} \cdot R_e^W , \tag{14}$$

- overmatching case $\left(R_e^W > R_e^B\right)$:

$$R_e^{W(ov)} = K_W^{ov} \cdot R_e^W , \tag{15}$$

The change in state of stress also leads to conversion in crack resistance in these zones, the procedure of destruction and kind of fracture. For example consider the above - mentioned problem when the crack is located in the middle part of the layer parallel to the interfaces and in the homogeneous material in which the constraint effect is not effecting.

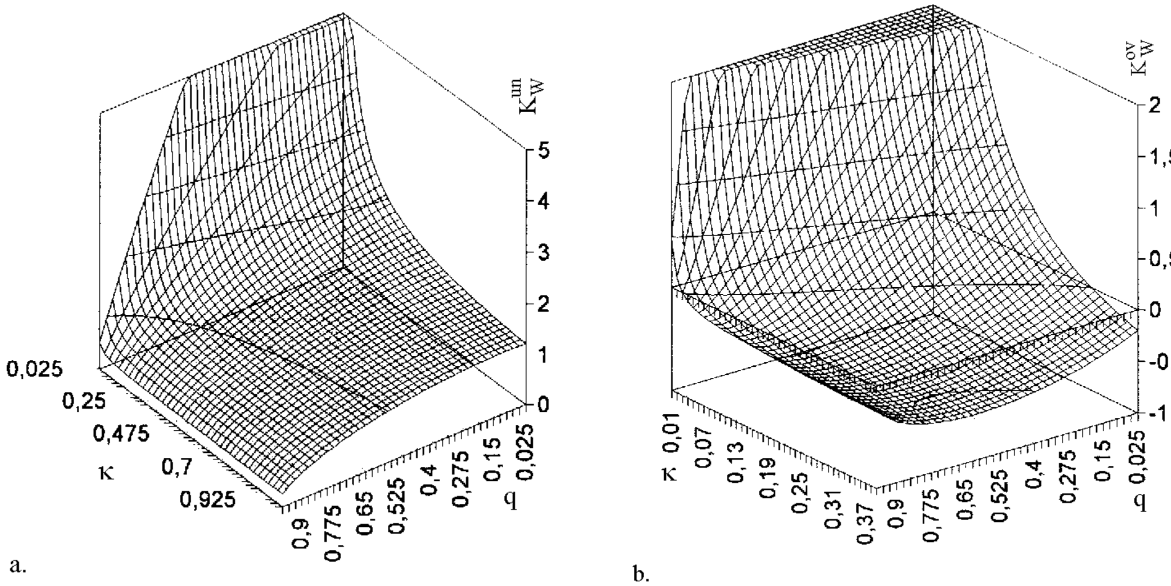

Fig. 3. Diagrams of K_W^{un} , K_W^{ov} for: (a) undermatched; (b) overmatched models of weld joints.

One of the most important procedures is the recently introduced Engineering Treatment Model (ETM) relates CTOD to the applied load or strain for work hardening materials [3, 4]. In according to the previously determined equations by Schwalbe for assessing the ratio of the driving forces in mismatching model - Fig. 1 and after taking the constraint factor $K_W^{un/ov}$. It will be able to determine the normalised parameter $\delta_R = \delta_W / \delta_B$ as follows:

- undermatching case at matching ratio $K_S = R_e^B / R_e^{W(un)} > 1$:

$\sigma_1 < R_e^{W(un)} < R_e^B$

lower limit: $$\delta_R = K_S, \tag{16}$$

upper limit: $$\delta_R = \frac{3}{2} \frac{1}{\frac{1}{K_S} + \frac{1}{2K_S^3}}, \tag{17}$$

$R_e^B > \sigma_1 \geq R_e^{W(un)}$ $$\delta_R = \left(\frac{K_W^{un}}{K_S} \right)^{\left(1 - \frac{1}{n_W}\right)}, \tag{18}$$

$\sigma_1 \geq R_e^B \geq R_e^{W(un)}$ $$\delta_R = \left(\frac{K_W^{un}}{K_S} \right)^{\left(\frac{1}{n_W} - \frac{1}{n_B}\right)} \left(\frac{1}{K_S} \right)^{\left(1 - \frac{1}{n_W}\right)}, \tag{19}$$

- overmatching case at matching ratio: $K_S = R_e^B / R_e^{W(un)} < 1$:

$\sigma_1 < R_e^B < R_e^{W(ov)}$

lower limit: $$\delta_R = K_S\,, \tag{20}$$

upper limit $$\delta_R = \frac{K_S\left(2 + K_S^2\right)}{3}\,, \tag{21}$$

$R_e^{W(ov)} > \sigma_1 \geq R_e^B$ $$\delta_R = \left(\frac{K_W^{ov}}{K_S}\right)^{\left(1-\frac{1}{n_B}\right)}, \tag{22}$$

$\sigma_1 \geq R_e^{W(ov)} \geq R_e^B$ $$\delta_R = \left(\frac{K_W^{ov}}{K_S}\right)^{\left(\frac{1}{n_W}-\frac{1}{n_B}\right)}\left(\frac{1}{K_S}\right)^{\left(1-\frac{1}{n_W}\right)}, \tag{23}$$

The results of this study of mismatched weld joints reveals high dependence of the fracture parameter δ_R according to equations (16)÷(23) on the such parameters as $K_W^{un/ov}$, K_S and n_W, n_B.

Conclusions

Constraints are of important in determining the mechanical of weld structures in many respects - microscopical and macroscopical scale. There are presenting a brief consideration of the constraint effect in relation microstructure - mechanical properties and the same problem was account in the macroscopic scale of the heterogeneous weld joints. After characteristic of the stress state there was made an analytical assessment of the fracture resistance of an undermatched and overmatched weld joints and reveals dependence of driving forces ratio δ_R according to equations (16)÷(23) on the such parameters as constraint factors $K_W^{un/ov}$, matching K_S and strain hardening exponents n_W, n_B.

The thus determined parameter δ_R gives the basic information about how in simple way to choose the critical parameter CTOD in mismatched weld joints for having strength equal to base metal.

References

[1] Bhadeshia H.K.D.H., *Mathematical Modelling of Weld Phenomena 3*, Cambridge, UK, pp. 249 ÷ 284, (1997).

[2] Ranatowski E., *Influence of the constraint effect on fracture resistance of mismatched weld joints*, Mechanism and Mechanics of Damage and Failure, ECF-11, United Kingdom, EMAS, Vol.3, pp. 2061 ÷ 2066, ISBN 0947817 - 93X, (1996).

[3] Ranatowski E., *Some remarks on stress state at interface of the mismatched weld joints*, Mis - Matching of Interfaces and Welds. Editors: K.-H. Schwalbe, M. Koçak, GKSS Research Center Publication, Geesthacht, FRG, ISBN 3-00-001951-0, pp. 185 - 196, Germany, (1997).

[4] Schwalbe K.-H., *Effect of weld metal mis-match on toughness requirements: some simple analytical considerations using the Engineering Treatment Model (ETM),* International Journal of Fracture, pp. 257 ÷ 277, Nr 56, (2005).