CONSTRAINT EFFECT AND FRACTURE OF MISMATCHED WELD JOINTS.

E. Ranatowski

Technical University, Mechanical Department,
St. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland

ABSTRACT

The paper deals with some aspects of the fracture resistance of mismatched weld joints with taken into consideration the constraint effect. At first the attention is focused on the relation between microstructure and selected mechanical properties. Physical models for the development of microstructure have the potential of revealing new phenomena and properties. This aspect is illustrated with presenting a brief consideration of the constraint effect in relation: microstructure - mechanical properties. The same problem is account in the macroscopic scale of the heterogeneous weld joints. After formulating a simplified model of mismatched weld joints a concise review of stress was made at interface between zones (W) and (B). Conclusion from above analysis form a constraint parameters $K_W^{un/ov}$ which were used to an assessment of the fracture parameters such as ratio of driving forces δ_R^{un} and δ_R^{ov}.

INTRODUCTION

In recent years the study of fracture from microstructure of materials by means of modern theoretical physical methods is an active field in the theory of fracture. A rational approach towards the design of welding alloys, joints and procedures can benefit from the development of quantitative and reliable models. Considering the completeness of theory and the practical necessity of weld joints designing for strength, fracture toughness, some questions must be answered. One is how the macromechanical quantities can be derived from the microscopic mechanism taking into account local structural heterogeneous fluctuation of materials in weld joints. Another is how deduce a quantitative description of the strength toughness properties of a welded joints with non-matching weld metal or HAZ. Obviously, this is a complicated and difficult problem to be solved.

Above question is very important under joint design of engineering structures. Welding is probably the most popular manufacturing process for joining metals used in structural applications. Some groups of weld joints are often highly inhomogeneous. For example this can the place during the welding of toughened steel and strain or age hardened steel, etc. 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. 1a. Strength mismatching occurs as an overmatching - fig. 1b 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. 1a. 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.

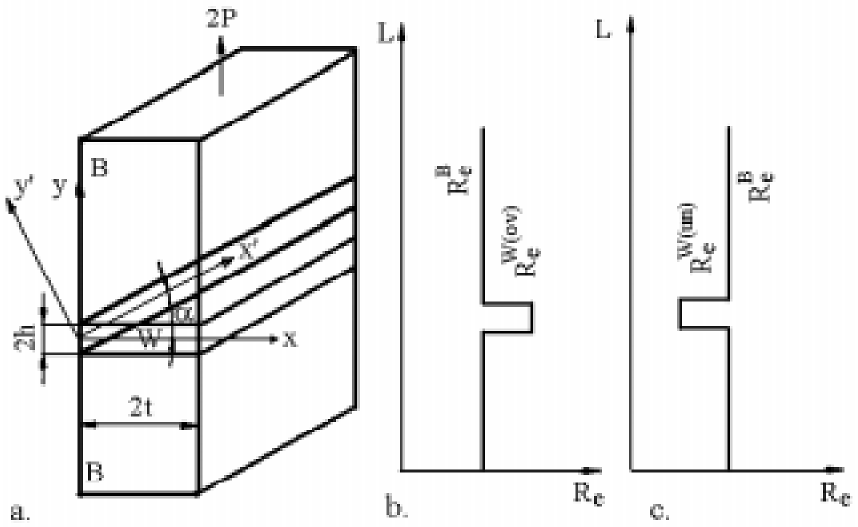


Figure 1. General characteristic of the models of the mismatched weld joints:
a. geometrical configuration - layer W as perpendicular or incline to external load 2P,
b. change of the yield point $R_e^{W\,(ov)}$ in the overmatched weld joint,
c. change of the yield point $R_e^{W\,(un)}$ in the undermatched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

INFLUENCE OF THE CONSTRAINT EFFECT ON THE MECHANICAL PROPERTIES OF THE MATERIAL MICROSTRUCTURE.

The general theory of constrained materials in classical mechanics of deformable media is characterised by a restriction on the class of possible motions. The level of constraint of homogeneous system depends upon:
- the body configuration,
- the type and magnitude of applied load,
- the material stress - strain properties.

The level of constraint heterogeneous system furthermore depends on physical phenomena at the interface of zones with different mechanical properties and their geometric configuration.
Constraint effects are of important determining the mechanical behaviour of weld structures in many respects - microscopical and macroscopical scale of analysed physical phenomena and in further part it will be quantatively assessment by using appropriate models. The modelling approach to the design of materials and processes is important and in great demand by industry because empirical experiments are now too expensive. The ideal models are those base on solid physical principles. A practically useful method is always one which is a compromise between basic science and empiricism. Then it may be reasonable to assume that strength of steel microstructure can be factorised into a number of intrinsic components [1]:

$$\sigma = \sigma_{Fe} + \sum_i x_i \sigma_{SS_i} + x_C \sigma_C + K_L \{L\} + K_D \rho_D^{0,5} \qquad (1)$$

$K_L\{\bar{L}\}$ - function for stengthening due to grain size,
K_D - coefficient for strengthening due to dislocations 7,34 x 10^{-6} MNm^{-1},
σ_{Fe} - strength to pure, annealed iron, 219 MNm^{-2} at 300 K,
σ_{SS_i} - substifutional solute (i) strengthening,
σ_C - solid solution strengthening due to carbon,
ρ_D - dislocation density, typically $10^{-16} m^{-2}$,
$\bar{L}$ - measure of the ferrite plate size, typically 0,2 μm,
x_i - the concentration of a substitutional solute which is represented here by a subscript i.

Furthermore, 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:

$$\sigma = V_\alpha \sigma_\alpha + V_b \sigma_B + V_p \sigma_p + V_M \sigma_M + V_\gamma \sigma_B + \dots \tag{2}$$

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 figures 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.

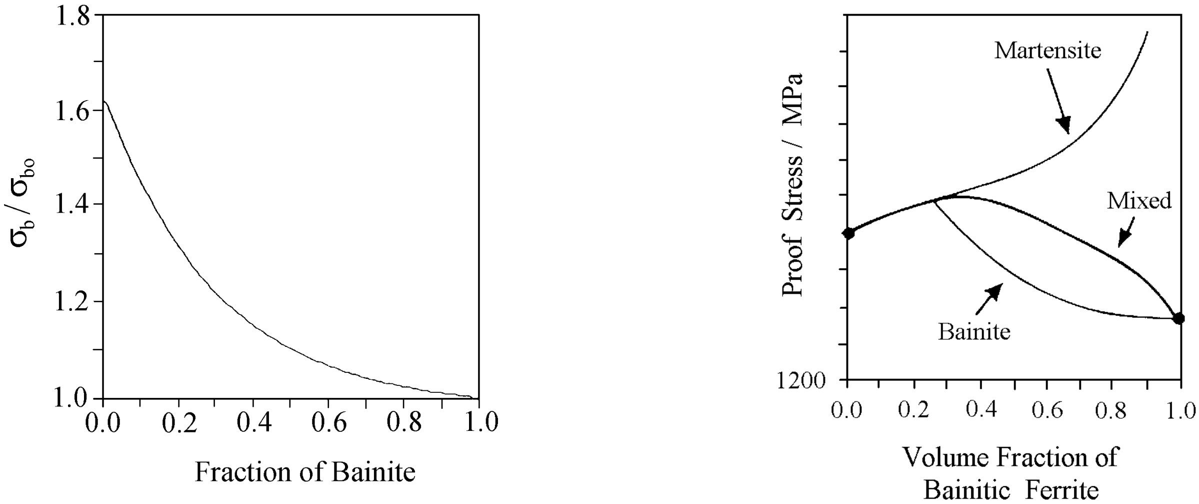


Figure 2. Characteristic of the strength of constrained bainite in martensite matrix [1]:
a. the normalised strength of bainite as the fraction of bainite in martensitic matrix,
b. the strength contributions of bainite and martensite in the mixed microstructure which has been tempered.

Then the strength of constrained bainite is established as follows [1]:

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

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.

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.

INFLUENCE OF CONSTRAINT EFFECT ON THE FRACTURE OF HETEROGENEOUS WELD

JOINTS - MACROSCOPIC SCALE.

The macro - mechanical heterogeneity of welded structures is one of their primary features. The heterogeneous nature of the weld joints are characterised by macroscopic dissimilarity in mechanical properties. This mis - match causes constrains in macroscopic scale and stress concentrations which are enhanced by geometric and physical parameters of the mismatched weld joints and state of loading - under tension or bending loading. 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:

$$\gamma + 1 = 2q \;\rightarrow\; \gamma = 2q - 1 \tag{4a, b}$$

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

- undermatching case:

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

$$-2\sqrt{1-\left(q+(1-q)\frac{\eta}{\kappa}\right)^2} \tag{5}$$

$$\sigma^{un}_{yy(rel)} = \frac{\sigma^{un}_{yy}}{k} = \frac{1}{2(1-q)}\left[\frac{\pi}{2} + 2(1-2q)\sqrt{q(1-q)} - \arcsin(2q-1)\right] + (1-q)\frac{\xi}{\kappa} \tag{6}$$

$$\sigma^{un}_{xy(rel)} = \frac{\sigma^{un}_{xy}}{k} = q + (1-q)\frac{\eta}{\kappa} \tag{7}$$

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

- overmatching case

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

$$\left. -2\sqrt{1-\left(q+(1-q)\frac{\eta}{\kappa}\right)^2}\,\right] \tag{8}$$

$$\sigma^{ov}_{yy(rel)} = \frac{\sigma^{ov}_{yy}}{k} = \frac{1}{2(1-q)}\left[-\frac{\pi}{2} - 2(1-2q)\sqrt{q(1-q)} + \arcsin(2q-1)\right] + (1-q)\frac{\xi}{\kappa} \tag{9}$$

$$\sigma^{ov}_{xy(rel)} = \frac{\sigma^{ov}_{xy}}{k} = q + (1-q)\frac{\eta}{\kappa} \tag{10}$$

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

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:

$$\tau_Q = \frac{\sigma_1}{2} \sin 2\alpha \tag{11}$$

where: $\sigma_1 = 2P/A$

- 2P - tensile force, fig.1,
- A = 2 t · L - cross - section perpendicular to 2P,
- α - angle, fig. 1.

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

$$q = \frac{\sigma_1}{2k} \sin 2\alpha \tag{12}$$

The σ_1 can assess the following values for undermatching case:

a. B - elastic, W - elastic

$$\sigma_1 < R_e^W < R_e^B \tag{13}$$

b. B - elastic, W - plastic

$$R_e^W \leq \sigma_1 < R_e^B \tag{14}$$

c. B and W - plastic

$$\sigma_1 > R_e^B > R_e^W \tag{15}$$

For overmatching case the σ_1 can assess the following values:

a. B - elastic, W - elastic

$$\sigma_1 < R_e^B < R_e^W \tag{16}$$

b. B - plastic, W - elastic

$$R_e^B \leq \sigma_1 < R_e^W \tag{17}$$

c. B and W - plastic

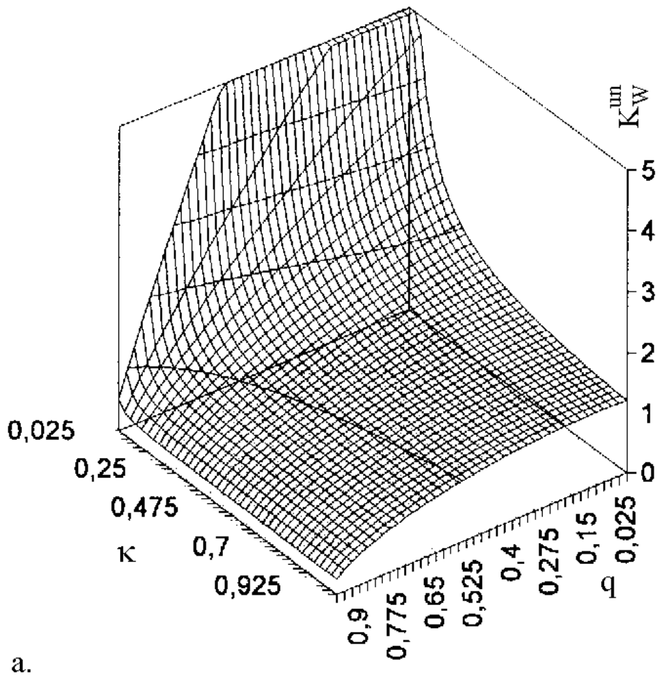
$$\sigma_1 > R_e^W > R_e^B \tag{18}$$

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:

$$K_W^{un} = \frac{2}{\sqrt{3}} \left(\frac{1}{4(1-q)} \left[\frac{\pi}{2} + 2(1-2q)\sqrt{q(1-q)} - \arcsin(2q-1) \right] + (1-q)\frac{1}{4\kappa} \right) \tag{19}$$

$$K_W^{ov} = \frac{2}{\sqrt{3}} \left(\frac{1}{4(1-q)} \left[-\frac{\pi}{2} - 2(1-2q)\sqrt{q(1-q)} + \arcsin(2q-1) \right] + (1-q)\frac{1}{4\kappa} \right) \tag{20}$$

Figure 3 a, b presents the dependence of the constraint factors $K_W^{un/ov}$ on the parameters κ and q.



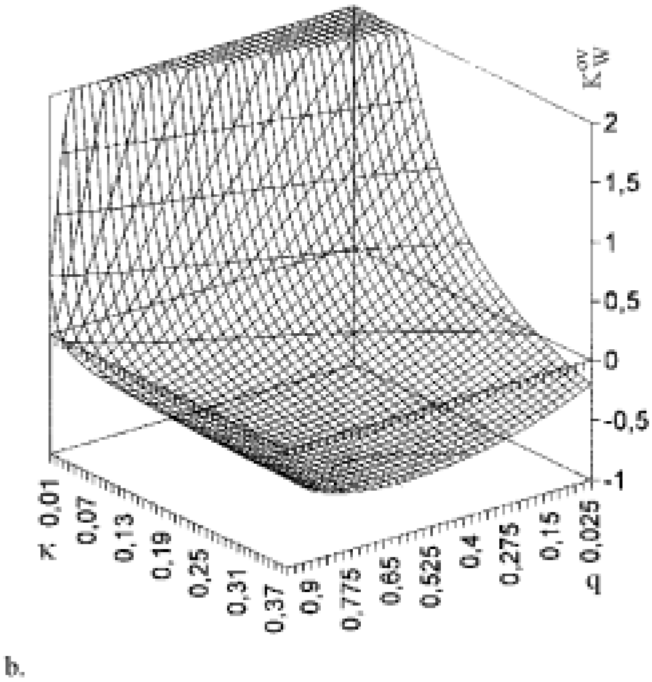


Figure 3. Diagrams of K_W^{un}, K_W^{ov} for:
a. undermatched, b. overmatched
models of weld joints.

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

$$R_e^{W\,(un)} = K_W^{un} \cdot R_e^W \tag{21}$$

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

$$R_e^{W\,(ov)} = K_W^{ov} \cdot R_e^W \tag{22}$$

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.

We can assessment the change of the size $r_p^{un/ov}$ of the plastic zones at the crack tip for layer $\left(R_e^W\right)$ normalised by r_p for homogeneous materials $\left(R_e^H\right)$ unconstrained at $R_e^W = R_e^H$ and at the same thickness of plates as [3]:

$$\frac{r_p^{un}}{r_p} = \frac{1}{\left(K_W^{un}\right)^2} \quad \text{or} \quad \frac{r_p^{ov}}{r_p} = \frac{1}{\left(K_W^{ov}\right)^2} \tag{23 a, b}$$

Figure 4 a, b presents the characteristic of the normalised size of the plastic zone at crack tip for the under- and overmatched cases. It should be noted that in the layer (W) favourable conditions for passing from plane stress to plane strain occur when the value of $K_W^{un/ov}$ is increased what is made by constraint effect.

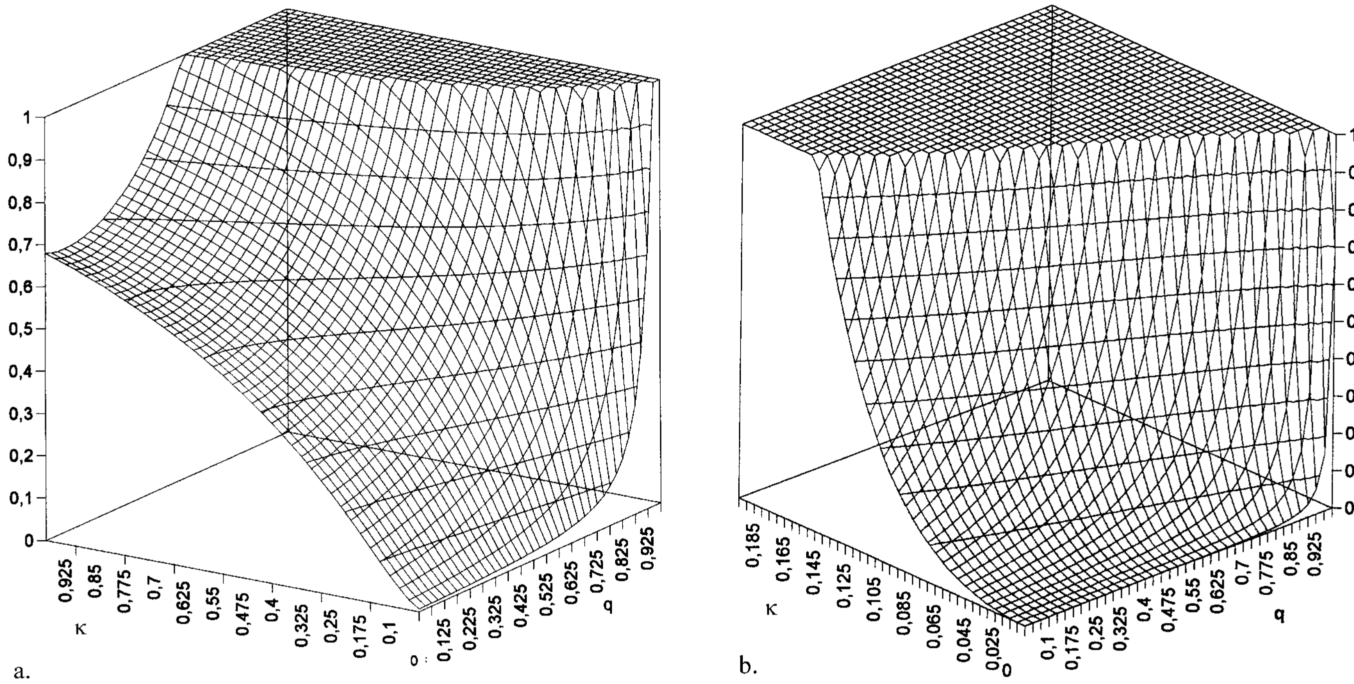


Figure 4. Normalised size of: a. r_p^{un} / r_p , b. r_p^{ov} / r_p respectively for undermatched and overmatched models of weld joints.

Above conclusions are very useful to assess a appropriate design concept against fracture initiation from crack like defects in weldments. 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 [4]. In according to the previously determined equations by K.-H. 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:
$$\delta_R = K_S \tag{24}$$

upper limit:
$$\delta_R = \frac{3}{2} \frac{1}{\frac{1}{K_S} + \frac{1}{2K_S^3}} \tag{25}$$

$R_e^B > \sigma_1 \geq R_e^{W(un)}$
$$\delta_R = \left(\frac{K_W^{un}}{K_S} \right)^{\left(1 - \frac{1}{n_W}\right)} \tag{26}$$

$\sigma_1 \geq R_e^B \geq R_e^{W(un)}$
$$\delta_R = \left(\frac{K_W^{un}}{K_S} \right)^{\left(\frac{1}{n_W} - \frac{1}{n_B}\right)} \left(\frac{1}{K_S} \right)^{\left(1 - \frac{1}{n_W}\right)} \tag{27}$$

- 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: $$\delta_R = K_S \tag{28}$$

upper limit: $$\delta_R = \frac{K_S\left(2 + K_S^2\right)}{3} \tag{29}$$

$R_e^{W(ov)} > \sigma_1 \geq R_e^B$ $$\delta_R = \left(\frac{K_W^{ov}}{K_S}\right)^{\left(1 - \frac{1}{n_B}\right)} \tag{30}$$

$\sigma_1 \geq R_e^{W(ov)} \geq R_e^B$ $$\delta_R = \left(\frac{K_W^{ov}}{K_S}\right)^{\left(\frac{1}{n_W} - \frac{1}{n_B}\right)} \left(\frac{1}{K_S}\right)^{\left(1 - \frac{1}{n_W}\right)} \tag{31}$$

The results of this study of mismatched weld joints reveals high dependence of the fracture parameter δ_R according to equations (24) ÷ (31) 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 (24) ÷ (31) on the such parameters as constraint factors K_W^{un}, K_W^{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.: (1997) Mathematical Modelling of Weld Phenomena 3. Cambridge, UK, p. 249 ÷ 284.
2. Ranatowski E.: (1997) 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, p. 185 - 196, Germany.
3. Ranatowski E.: (1996) 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. p. 2061 ÷ 2066. ISBN 0947817 - 93X..
4. Schwalbe K.-H.: (1992) Effect of weld metal mis-match on toughness requirements: some simple analytical considerations using the Engineering Treatment Model (ETM). International Journal of Fracture, p. 257 ÷ 277, Nr 56.