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RELATION STRUCTURE – FRACTURE RESISTANCE IN PROCESS OF ESTIMATE THE WELDABILITY OF LOW ALLOY STEELS

PART I

ABSTRACT

The relationship between microstructure and mechanical properties of structural materials is still relevant problem in the theory of materials science and mechanical engineering. The question is how the macro-mechanical parameters can be derived from the microscale mechanisms taking into account local structural heterogeneities. Another question is how to make quantitative descriptions of the strength and toughness properties of welded joints made of non-matching weld metal. These problems are the objects of welding and mechanical investigation and they are related to estimation of weldability. The results of this study concern the evaluation stress state at interface of the under- and overmatched weld joints. After formulating a simplified model of under- and overmatched weld joints an analysis was made of stress at interface for the cases of perpendicular and non - perpendicular orientation of the zones (soft - layer and hard - layer) relative to the load action direction under tension.

Key words: *weldability of steels, fracture, stress state, fracture mechanics*

INTRODUCTION

For some groups of welded joints, considerable local diversification of the material structure and, consequently, of the mechanical properties may occur in the weld or in the heat – affected zone (HAZ). This can take place during the welding of toughened steel, and strain or age hardened steel, etc.

The heterogeneous nature of the weld joints are characterized 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.

Considering the above - mentioned problem of a heterogeneous weld joints we will focus our attention on a simplified theoretical model which is presented on Fig. 1.

The essential physical phenomena affecting the mechanical properties of this model occur at the interface of zones (B) and (W). Determination of change in the state of stress occurring in that area is of primary importance for a correct interpretation and estimation of mechanical properties of this model. After setting the assumption

according to rules determined in [1] a stress analysis was made in agreement with principles of the mechanics of solids.

Fig. 1. General characteristic of the model of the mismatched weld joints:
a. geometrical configuration, b. change of the yield point in the undermatched weld joint,
c. change of the yield point in the overmatched weld joint

Components of the state stress in mis - matched weld joints under static tension are determined by the equilibrium equations and the equation of the plasticity condition which fulfilling the boundary condition on the interface of zones (B) and (W). The stress state was determined as a function of physical parameters: k , $\gamma = k_1 / k$, $k_1 < k$ and geometrical parameters: κ , η , ξ . The parameter γ also determined the influence of inclination of the layer on stress state.

Finally, from the stress state parameter S_p as physical measure of the deformation and effort of the mismatched welds and SINTAP programme overview are presented.

CHARACTERISATION OF THE MIS-MATCH WELDED JOINT MODEL – ASSUMPTION AND SIMPLIFICATION

Considering the above-mentioned of mis-match welded joints, it is essential that a model which shows the real condition of joint is presented. It should be assumed that the model presents the physical reality precisely enough to ensure the physical or technical sense of the model analysis. Thus, the physical model is a simplification of the real welding system and only matches the system in respect of its essential features. A suitable model to analyse the structure of a welded joint of, e.g., toughened steel is presented in Fig. 1. The layer of reduced mechanical strength imitates the weld or a part of the HAZ. The essential physical phenomena affecting the mechanical properties of this model occur at the interface of zones (B) and (W). Determination of changes in the state of stress occurring in this area is of primary importance for a correct interpretation and estimation of mechanical properties, e.g., during static tension. The main difficulty adequately estimating the state of stress is that the material of an undermatched weld joint undergoes heterogeneous deformation which result in non-uniform stress pattern. It is possible for discontinuities of stresses to arise, but these should not disturb the equilibrium state. Such discontinuities occur when some stress components, having

passed through a definite surface inside the joint, the so-called stress discontinuity surface, stress show a jump, i.e., they change their value and direction on each the two sides of the surface (Fig. 2).

Fig.2. Stress distribution at the interface

In the state of equilibrium the stress components σ_η and τ_η are the same on both sides of the stress discontinuity surface, while the remaining components may be different and even of opposite signs. However, the equilibrium of the element is not disturbed and, therefore, such discontinuities are permissible in static conditions.

The model was built on the assumption that the materials used are of ideal plasticity. In particular, it should be emphasised that when such a theoretical model of a joint is considered, it is possible for high jump of stresses to occur. It should also be pointed out that, in spite of considerable simplifications of the physical phenomena arising in the system, the results obtained with the theoretical model have been confirmed by experimental work. In almost every case they give a good idea about deformations and stresses inside a welded joint [2].

It was found that, in order to satisfactorily compare the model of a joint and mismatched weld joint the essential physical phenomena in the model and the real joint must be described using the same differential equations and in accordance with the criteria of similarity.

CHARACTERISTIC OF THE STRESS STATE AT INTERFACE OF THE UNDERMATCHED WELD JOINTS

Fig. 3a presents the generally characteristic of stress state in undermatched weld joints. The components σ_x , σ_y and τ_{xy} for the undermatched weld joints can be determined as follows:

$$\sigma_x = k \cdot \left[\left(C + \frac{1-\gamma}{2} \cdot \frac{x}{h} \right) - 2 \cdot \sqrt{1 - \left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2} \cdot \frac{y}{h} \right)^2} \right] \quad (1)$$

$$\sigma_y = k \cdot \left(C + \frac{1-\gamma}{2} \cdot \frac{x}{h} \right) \quad (2)$$

$$\tau_{xy} = k \cdot \left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2} \cdot \frac{y}{h} \right) \quad (3)$$

where:

C - parameter as a function of γ ,

$$\gamma = \frac{k_1}{k} ; |\gamma| \leq 1 ; k = \frac{R_e^{W(un)}}{\sqrt{3}} ; -k \leq k_1 \leq k ; R_e^{W(un)} \leq R_e^B ,$$

$R_e^{W(un)}$ - yield point of the weld or part of HAZ of the undermatched weld joints,

R_e^B - yield point of the base material.

Fig. 3a. Characteristic of the external field of force and stress distribution of the undermatched weld joints: a. for inclination of soft layer ; b. for perpendicular soft layer; c. internal stress

Fig. 3b. Characteristic of the external field of force and stress distribution of the overmatched weld joints [1]: a. for inclination of soft layer ; b. for perpendicular soft layer; c. internal stress

The tangential stress at interface are heterogeneous, expressed by $k = \tau_{xy}$ and $k_l = \tau_{xy}$, where k means the shear yield point what is a difference with reference to the Prandtl model. The boundary values of the tangential stress k and k_l on the interfaces result from the action of the tangential stresses τ_k and τ_{2Q} to be follows:

$$k_l = \tau_{xy} = f_1(\tau_k, \tau_{2Q}) \quad (4)$$

for $x < l \wedge y = +h$ and $x > l \wedge y = -h$

$$k = \tau_{xy} = f_2(\tau_k, \tau_{2Q}) \quad (5)$$

for $x < l \wedge y = -h$ and $x > l \wedge y = +h$

where:

- τ_k - tangential stress arising on the interface and resulting from the action of the $2Pn$ force,
 τ_{2Q} - tangential stress resulting from the presence of tangential force component the $2Q$.

If the layer (W) is perpendicular to the line of the force $2P$ ($\alpha = 0$) only the tangential stress $\tau_k = \tau_{2Q}$ arise at the interface – Fig. 3b.

Parameter C to be determined by the Saint - Venant condition of the absent of normal stress at the cross section of the layer at $x = 0$ as follows:

$$\int_{-h}^{+h} (\sigma_x)_{x=0} dy = 0 \quad (6)$$

Inserting Eqn. (1) and (6) we obtain the parameter C as follows:

$$C = \frac{I}{I - \gamma} \left(\frac{\pi}{2} - \gamma \sqrt{1 - \gamma^2} - \arcsin \gamma \right) \quad (7)$$

According to Eqns (1), (2) the parameter C very intensive influences on the stress state at interface of zones (B) and (W). The parameter C as a function of γ has been presented on the Fig. 4 and some values of $C(\gamma)$ are given in Tab. 1.

Table 1. Values of $C(\gamma)$ for undermatched weld joint

γ	$C(\gamma)$	γ	$C(\gamma)$	γ	$C(\gamma)$
- 0,99	1,578	- 0,3	1,663	0,25	1,435
- 0,85	1,64	- 0,1	1,61	0,55	1,176
- 0,7	1,674	1,571	0,75	0,75	0,907
- 0,5	1,685	0,1	1,523	0,99	0,188

a.

b.

Fig. 4. Characteristic of the parameter C as a function of γ for: a. under- , b. overmatched weld joints

After inserting (9) to (1), (2) and introducing the relative parameters κ , η , ξ we obtain the stress characteristic as follows:

$$\sigma_{x(rel)} = \frac{\sigma_x}{k} = \frac{1}{1-\gamma} \left(\frac{\pi}{2} - \gamma \sqrt{1-\gamma^2} - \arcsin \gamma \right) + \frac{1-\gamma}{2} \frac{\xi}{\kappa} - 2 \sqrt{1 - \left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2} \frac{\eta}{\kappa} \right)^2} \quad (8)$$

$$\sigma_{y(rel)} = \frac{\sigma_y}{k} = \frac{1}{1-\gamma} \frac{1}{1-\gamma} \left(\frac{\pi}{2} - \gamma \sqrt{1-\gamma^2} - \arcsin \gamma \right) + \frac{1-\gamma}{2} \frac{\xi}{\kappa} \quad (9)$$

$$\tau_{xy(rel)} = \frac{\tau_{xy}}{k} = \frac{1+\gamma}{2} + \frac{1-\gamma}{2} \frac{\eta}{\kappa} \quad (10)$$

where: $\kappa = \frac{h}{l} \rightarrow h = \kappa \cdot l$; $\eta = \frac{y}{l} \rightarrow y = \eta \cdot l$; $\xi = \frac{x}{l} \rightarrow x = \xi \cdot l$

and we can evaluate the relative state of stress of the soft layer (Fig. 3a) as a function on the parameter γ and geometrical relative parameters κ , η , ξ .

The equation of plasticity condition allow to determined the relationship between τ_{xy} and k as follows [1]:

$$|\tau_{xy}| \leq k \quad (11)$$

what is agreement with Tresca assuming. The value of k may be attained only on a part of the interface as statement above.

Furthermore the value under square root in eq.(8) must satisfy a condition:

$$-1 \leq \frac{1+\gamma}{2} + \frac{1-\gamma}{2} \frac{\eta}{\kappa} \leq 1 \quad (12)$$

Then the geometrical relationship between η and κ yield:

$$\kappa \geq \eta \quad (13)$$

If $\gamma = -1$, the Eqns (8)÷(10) assumes the form previously determined by Prandl and if $\gamma = 1$, $\sigma_x = \sigma_y = 0$, $\tau_{xy} = k$.

For example Fig. 5 presents the characteristic of the stress state in according to equations (8), (9), (10) as a functions of γ at $\kappa = 0,3; 0,5; 0,75; 0,99$ and $\eta = 0,3$; $\xi = 0,1$ at $-1 < \gamma < 1$.

In this situations at first the relative stresses $\sigma_x^{(rel)}$, $\sigma_y^{(rel)}$ increases up to attain the maximum values of $\sigma_x^{(rel)}$, $\sigma_y^{(rel)}$ when γ decreases. After attain the maximum the values of $\sigma_x^{(rel)}$, $\sigma_y^{(rel)}$ are decreases. The tangential stress $\tau_{xy}^{(rel)}$ is decreases at $-1 < \gamma < 1$. At $\eta = \kappa$ the value of relative tangential, stress is constant: $\tau_{xy}^{(rel)} = 1$.

Fig. 5. Stresses $\sigma_x, \sigma_y, \tau_{xy}$ at interface of undermatched weld joint at: $\kappa = 0,3; 0,5; 0,75; 0,99$

and $\eta = 0,3$; $\xi = 0,1$ at $-1 < \gamma < 1$

It should be noted that the components of the state of stress at interface of weld (W) and base metal (B) causes change in the mechanical action of stress and mechanical properties of the material in the area of a heterogeneous system. For example a change in the state of stress leads to a change in crack resistance in this zones [2].

CHARACTERISTIC OF THE STRESS STATE AT INTERFACE OF THE OVERMATCHED WELD JOINTS

Characteristic of the situation in the overmatching weld joint has been presented on the Figs. 1c and 2b. The components of stress state $\sigma_x, \sigma_y, \tau_{xy}$ for the overmatching weld joints to be determined as follows:

$$\sigma_x = - \left[k \left(C + \frac{1-\gamma}{2} \frac{x}{h} \right) + 2k \sqrt{1 - \left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2} \frac{y}{h} \right)^2} \right] \quad (14)$$

$$\sigma_x = k \left(C + \frac{1-\gamma}{2} \frac{x}{h} \right) \quad (15)$$

$$\sigma_x = k \left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2} \frac{y}{h} \right) \quad (16)$$

where:

C - parameter as a function of γ ,

$$\gamma = \frac{k_1}{k} ; |\gamma| \leq 1 ; k = \frac{R_e^{W(ov)}}{\sqrt{3}} ; -k \leq k_1 \leq k ; R_e^{W(ov)} > R_e^B ,$$

$R_e^{W(ov)}$ - yield point of the weld or part of HAZ of the overmatched weld joints,

R_e^B - yield point of the base material.

Parameter C to be determined similarly as in like manner in the undermatched weld joints by using the Saint-Venant condition in accordance with Eqn. () and (14) yield:

$$C = \frac{1}{1-\gamma} \left(-\frac{\pi}{2} + \gamma \sqrt{1-\gamma^2} + \arcsin \gamma \right) \quad (17)$$

The parameter C as a function γ has been presented on Fig. 4b and some values of $C(\gamma)$ are given in Tab. 2.

Table 2. Values of $C(\gamma)$ for overmatched weld joint

γ	$C(\gamma)$	γ	$C(\gamma)$	γ	$C(\gamma)$
- 0,99	-1,578	- 0,6	-1,684	0	-1,571
- 0,9	-1,623	- 0,545	-1,686	0,2	-1,467
- 0,8	-1,654	-0,5	-1,685	0,4	-1,321
- 0,7	-674	-0,4	-1,678	0,99	-0,188

According to Eqns (14) and (15) the parameter C also very intensive influences on the stress state at interface and he is causing a non-linear stress state of σ_x, σ_y . When the value of γ decrease up to $\gamma = -0,538$, the value of C also decrease. At $\gamma = -0,538$, the value of C has a minimum. At $\gamma = -0,538$, the value of C increases.

After inserting (17) to (14), (15) and introducing the relative parameters κ, μ, ξ we obtain the stress characteristic as follows:

$$\sigma_{x(rel)}^{ov} = \frac{\sigma_x^{ov}}{k} = - \left[\frac{1}{1-\gamma} \left(-\frac{\pi}{2} + \gamma \sqrt{1-\gamma^2} + \arcsin \gamma \right) + \frac{1-\lambda}{2} \frac{\xi}{\kappa} + 2 \sqrt{I \left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2} \frac{\eta}{\kappa} \right)^2} \right] \quad (18)$$

$$\sigma_{y(rel)}^{ov} = \frac{\sigma_y^{ov}}{k} = - \frac{1}{1-\gamma} \left(-\frac{\pi}{2} + \gamma \sqrt{1-\gamma^2} + \arcsin \gamma \right) + \frac{1-\lambda}{2} \frac{\xi}{\kappa} \quad (19)$$

$$\tau_{xy(rel)} = \frac{\tau_{xy}}{k} = \frac{1+\gamma}{2} + \frac{1-\gamma}{2} \frac{\eta}{\kappa} \quad (20)$$

The overmatching weld joints must to satisfy the physical and geometrical conditions in according to Eqns. (11), (13).

Fig. 6 presents the characteristic of the stress state in agreement to Eqn. (18), (19), (20) as functions of γ .

Fig. 6. presents $\sigma_{x(rel)}, \sigma_{y(rel)}, \tau_{xy(rel)}$ at $\kappa = 0,3; 0,5; 0,75; 0,99$ and $\eta = 0,3; \xi = 0,1$ at $-1 < \gamma < 1$. When γ decreases the value of $\sigma_{x(rel)}$ is increases up to attain the minimum and $\sigma_{y(rel)}$ decreases up to attain the minimum. After attain the extreme values to occur reciprocal trend – the stress $\sigma_{x(rel)}$ has a downward trend and $\sigma_{y(rel)}$ has a upward trend. The tangential stress $\tau_{xy(rel)}$ is decreases at $-1 < \gamma < 1$. Only at $\eta = \kappa$ the value of $\tau_{xy(rel)} = 1$.

Fig. 6. Stresses $\sigma_x, \sigma_y, \tau_{xy}$ at interface of overmatched weld joint at: $\kappa = 0,3; 0,5; 0,75; 0,99$ and $\eta = 0,3$; $\xi = 0,1$ at $-1 < \gamma < 1$

CONCLUSIONS

The above analysis reveals the difference state of stress at interface of the under- and overmatched weld joints. This is making a change of mechanical properties of the difference part of the mismatched weld joints.

The paper also explains the sequential dependency of each of the physical processes in the welding situation. This weldability analysis is a new powerful research and development tool which is useful for metallurgistic technologist and design engineers.