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ANALYSIS OF THE MECHANICAL PROPERTIES OF UNDERMATCHED WELD JOINT

Key-words

Stress distribution, stress intensity factor K_{IC}, constraint factor K_W.

Summary

Available technical literature fails to give a suitable description of the specific relation between the toughness and common tensile property characteristics of weld metal and the performance characteristic of welded joints.

After formulating a simplified model of the situations in mismatched weld joints, a concise review of the state of stress at the interface between different zones in the weld metal or HAZ is presented. Conclusions from the above analysis from a constraint parameter K_W are used to assess the mechanical properties of mismatched weld joints with heterogeneous microstructures and fracture mechanics parameters.

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 main characteristic of welded joints is the load diversification of the material structure in the HAZ, which also appears as a diversification of the material hardness (Fig. 1a, b). Changes in the material structure are directly related to the mechanical properties in e.g., *Re* (tensile yield point) and *Rm* (tensile strength).

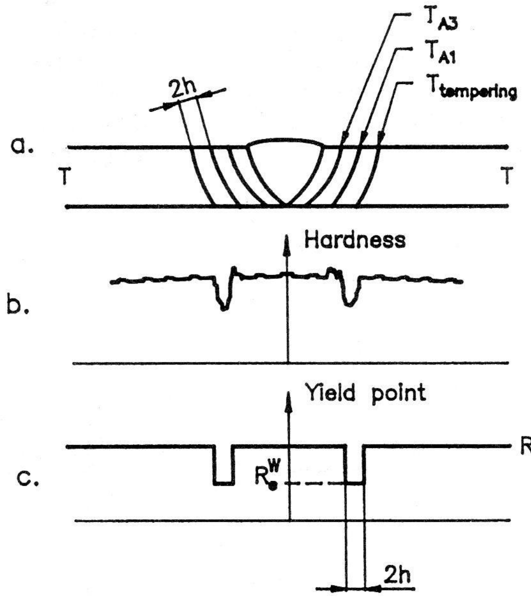


Fig. 1. Characteristic of the situation in the under-matched weld joint by: (a) distribution of the isotherms in head-affected zone (HAZ); (b) hardness penetration pattern; (c) yield point pattern

Constants, which characterise the elasticity of the material, show only slight changes, and it can be assumed that the E (Young's modulus), μ (shear modulus), and ν (Poisson's ratio) remain unchanged in every jointing zone. The effect of the welded joint's differentiated structure on its mechanical properties during static tension is discussed below.

1. Characterisation of the mismatched welded joint model – assumption and simplifications

Considering the above-mentioned problem of a mismatched welded joint, it is essential that a model which shows the real condition of the 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 made of, e.g., toughened steel, and is presented in (Fig. 1) and (Fig. 2). 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 (T) 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 in adequately estimating the state of stress is that the material of an undermatched weld joint undergoes heterogeneous deformations that result in non-uniform stress pattern. It is possible for discontinuities of stresses to arise, but these should not disturb the state of equilibrium. Such discontinuities occur when some stress components, having passed through a definite surface inside the joint, the "stress discontinuity surface," stress show a jump, i.e., they change their value and direction on each of the two sides of the surface (Fig. 3).

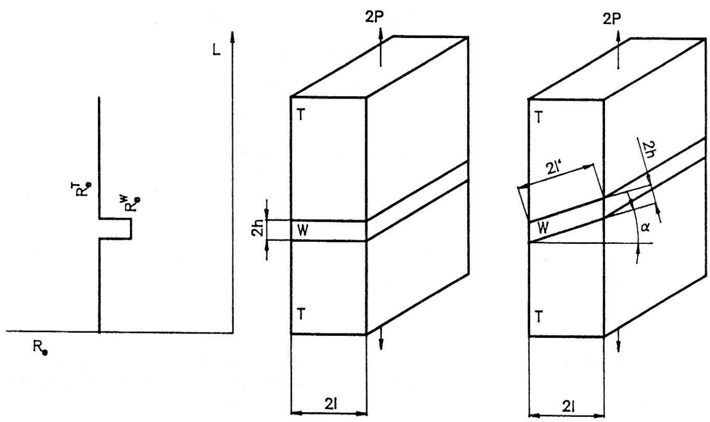


Fig. 2. General configuration of the model of the undermatched weld joint

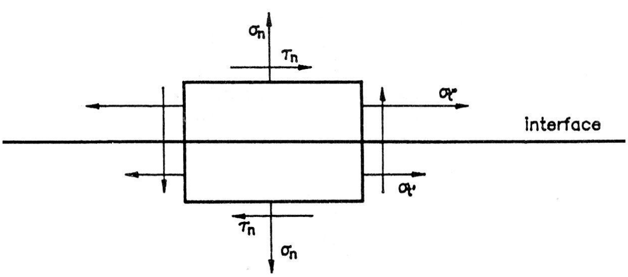


Fig. 3. Stress distribution at the interface

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; 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 jumps 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 research. In almost every case, they give a good information about deformations and stresses inside a welded joint.

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.

2. Characterisation of the state of stress and the mechanical properties of the undermatched weld joint model

It is necessary to create a mathematical model of the physical phenomena, which accompanies the loading process of the model described above. The mathematical model gives a description of the physical model mostly in the form of differential equations, which, in this instance, express the conditions of equilibrium and the properties of the joint materials related to them, e.g., the conditions of plasticity, and the boundary conditions. The solution of the equations leads to an estimation of the state of stress.

Figure 4 presents the characteristic of the force field and the adequate field of stresses in that are in accordance to [1, 2]. It should be noted that the reason for heterogeneous deformation and stresses in the model under discussion lies in the condition of the interfaces.

Because of the inclination of the layer ($\alpha > 0$), a change takes place in the form of the interfaces due to the appearance of the axial force $2P_n$ and the tangential 2Q.

The tangential stresses are heterogeneous, expressed by $k = \tau_{xy}$ and $k_1 = \tau_{xy}$ tangential stresses k and k_1 on the contact surfaces, result from the action of tangential stresses τ_k and τ_{2Q}

$$\tau_{xy} = f_1\left(\tau_k, \tau_{2Q}\right) = k_1 \tag{1}$$

For

$$x < 1' \wedge y = -h$$

$$x > 1' \wedge y = +h$$

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

for

$$x < 1 \wedge y = +h$$

$$x > 1 \wedge y = -h$$

where

τ_k – tangential stress arising on the interface and resulting from the action of the $2P_n$ force and inhibition of the deformation of the layer (W) by the more durable material (T) along the interface,

τ_{2Q} – tangential stress resulting from the presence of tangential force component 2Q.

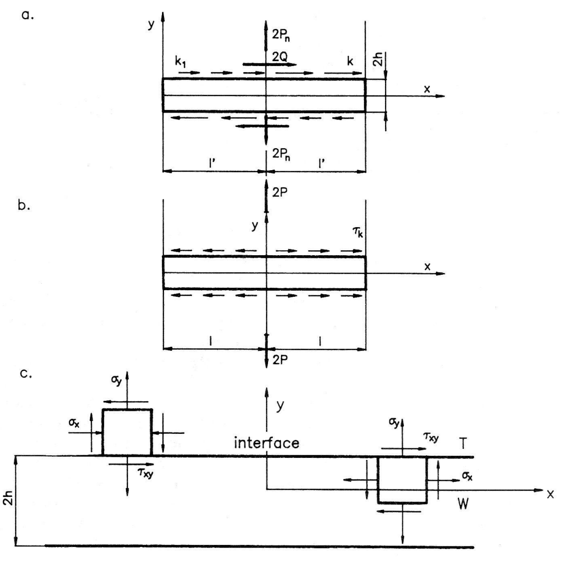


Fig. 4. Characteristic of the external field of force and the adequate field of stress distribution at the interfaces of the soft layer: (a) for inclination of soft layer; (b) for perpendicular soft layer; (c) change of internal stresses in nearness of interfaces

If the layer (W) is perpendicular to the line of the force 2P ($\alpha = 0$), only the tangential stresses $\tau_k = \tau_{xy}$ arise at the interface (Fig. 4). Such a change of stress in the layer (W) can have an advantageous effect on the whole strength of the welded joint. The components of the state of stress within the contact surface are determined by the equilibrium equations

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \tag{3a}$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} = 0 \tag{3b}$$

and the equation of the plasticity condition

$$(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2 = 4k^2 \tag{4}$$

which, by fulfilling the boundary conditions for τ_{xy} on y = ± h, allows the components σ_x, σ_y, and τ_{xy} to be determined as follows

$$\sigma_x = k\left[a + \frac{1-\gamma}{2}\frac{\xi}{\kappa} - 2\sqrt{\left\{1 - \left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2}\frac{\eta}{\kappa}\right)^2\right\}}\right] \tag{5a}$$

$$\sigma_y = k\left(-a - \frac{1-\gamma}{2}\frac{\xi}{\kappa}\right) \tag{5b}$$

$$\tau_{xy} = k\left(\frac{1+\gamma}{2} + \frac{1-\gamma}{2}\frac{\eta}{\kappa}\right) \tag{5c}$$

where

$$\kappa = h/l \qquad \gamma = k_1/k$$

$$\eta = y/l \qquad |\gamma| \le l$$

$$\xi = x/l \qquad x < l$$

$$a = \frac{1}{1-\gamma}\left\{\frac{\pi}{2} - \gamma\sqrt{(1-\gamma^2)} - \arcsin\gamma\right\}$$

From the practical point of view, the effect of the change in the state of stress on the mechanical properties of the welded joint model at static tension is very interesting. It can be expressed by the average values of stresses that can be transferred by a joint with a soft layer as

$$\sigma_{aver} = \frac{2R_e^W}{\sqrt{3}} \left\{ \begin{array}{l} \frac{1}{4(1-q)} \left[\frac{\pi}{2} + 2(1-2q)\sqrt{\{q(1-q)\}} - \arcsin(2q-1) \right] \\ + (1-q)\frac{1}{4\kappa} \end{array} \right\} \tag{6}$$

where

R_e^W is the tensile yield point of the layer (W)

q is the factor which allows for the effect of contact tangential stresses $q = Q / k \cdot l \cdot 1 \leq 1$

By converting the above equation and introducing the following ratio

$$K_W = \frac{\sigma_{aver}}{R_e^W} = \frac{2}{\sqrt{3}} \left\{ \frac{1}{4(1-q)} \left[\frac{\pi}{2} + \ldots \right] + (1-q)\frac{1}{4\kappa} \right\} \tag{7}$$

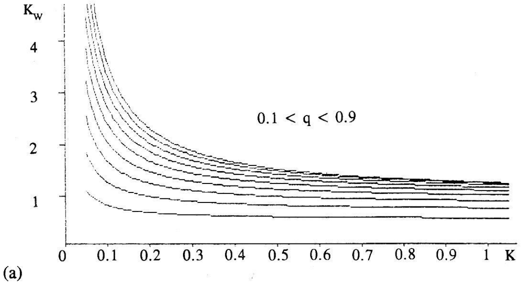
we can evaluate the effect of the change of mechanical properties of the soft layer (W) as a result of the change in the state of stress. Figure 5 presents the dependence of the parameter K_W on the parameter κ at $0.1 \leq q < 0.9$ and on the parameter q at $0.1 < \kappa < 0.9$. The above data indicate that the greater the value of K_W, the smaller the value of κ and q. If $q = 0$ ($2Q = 0$, $\alpha = 0$), equation (6) assumes the form previously determined by Kačanov [2].

$$\sigma_{aver} = \frac{2}{\sqrt{3}} R_W^e \left(\frac{\pi}{4} + \frac{1}{4\kappa} \right) \tag{8}$$

The theoretical values of K_W indicate that the mechanical properties of the "soft layer" can be considerably improved, due to the change in stresses of that area. Apart from the geometrical conditions, the upper limit of the strength is determined by the material in the zones (T) and (W).

If the mechanical properties of the material in the zone (T), determined as R_m^T (tensile strength) and R_e^T (tensile yield strength), correspond in principle with the mechanical properties of the material in its initial state before welding, and it is assumed that $\sigma_{aver} = R_m^T$, then the relative thickness of the layer (W), which has no negative effect on the whole strength of the welded joint, can be calculated from the following equation [3]:

$$\kappa_{cr} = \frac{1-q}{2\sqrt{3}(1-q)K_s \cdot \gamma^T - \left[\pi/2 + 2(1-2q)\sqrt{q(1-q)}\right) - \arcsin(2q-1)\right]} \tag{9}$$



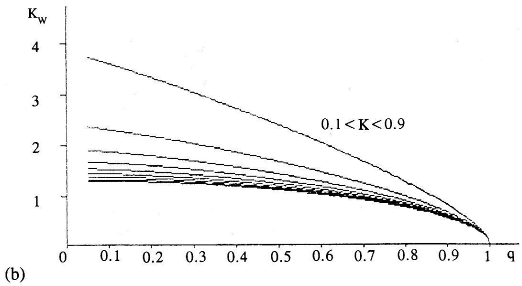


Fig. 5. value of parameter K_W: (a) as a function of κ at 0.1 < q <0.9; (b) as a function of q at 0.1 < κ <0.9

where:

$$K_s = R_e^T / R_e^W$$

$$\gamma^T = R_m^T / R_e^T$$

3. Effect of the angle of inclination of the layer (W) on the form of fracture

It is clear that a change in the state of stress in the soft layer (W) also causes a change in the mechanical action of stresses and the mechanical properties of the material in the area of a heterogeneous system. The consolidation of the soft layer causes a change in the state of stress which also leads to a change in crack resistance in these zones, the procedure of destruction, and the kind of fracture.
In principle, the procedure of cracking takes place in the layer (W). The fractures that arise can change from brittle at q = 0, α = 0 to ductile fracture at q > 0, α > 0. Conditions which cause brittle fracture can be determined, based on the conception of Pełczyński [3] as

$$\frac{\sigma_{aver}}{R_0} = \frac{\sigma_H}{\sigma_V} \tag{10}$$

where

R_0 is cohesive strength

σ_H, σ_v is the equivalent stress according to Huber-Mises de Saint-Venat, respectively.

The equivalent stress σ_H can be calculated from

$$\sigma_H = \frac{\sqrt{2}}{2}\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 - 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} \tag{11}$$

Instead of $\sigma_{v,}$ we can write

$$\sigma_v = \sigma_y - \nu(\sigma_x + \sigma_z) \tag{12}$$

Therefore, with regard to equation (8), we can evaluate the geometrical conditions of the layer (W) expressed by the parameter κ, which can be calculated from

$$\kappa = \frac{R_e^W \sigma_V}{2\sqrt{3}\sigma_H R_0 - \pi R_e^W \sigma_V} \tag{13}$$

The solution of the above equation gives a value for parameter κ after which brittle fracture may occur [4]. Undermatched weld joints fail in ductile mode in the soft layer when

$$\frac{\sigma_{aver}}{R_0} < \frac{\sigma_H}{\sigma_V} \tag{14}$$

We can now evaluate the geometrical conditions of the layer (W) expressed by parameter κ when the undermatched weld joints fail in the ductile mode [3]:

$$\kappa > \frac{R_e^W (1-q)\sigma_V}{2\sqrt{3}\sigma_H R_0 - R_e^W \sigma_V \times \left[(\pi/2) + 2(1-2q)\sqrt{\{q(1-q)\}} - \arcsin(2q-1)\right]} \tag{15}$$

If $\alpha \to 0$, $q \to 0$, the equation (15) assumes the form determined by equation (13). For an inclined layer, it is difficult to create ductile fracture in the form of slide-cracking. When such difficulties arise in relation to the planes on which maximum tangential stresses occur, or the energy of non-dilatational strain reaches its maximum value, considerably stronger stresses are required to create a shear fracture ($K_W > 1$).

Undermatched weld joints, in agreement with equation (13), fail in brittle mode in the soft layer and tend to be arranged perpendicular to the loading line. Undermatched weld joints, in agreement with inequality (15), ($\alpha > 0$, $q > 0$ and for small value of κ) fail in the soft layer in ductile mode in the form of slide-cracking. When parameter κ increases, the form of failure changes from slide-cracking to mixed cracking, i.e., to ductile-brittle fracture.

4. Some aspects of estimation of the K_C and K_{IC} values for the soft layer (W)

Regarding the previously accepted assumption concerning materials which create the heterogeneous welded joint model, $\sigma_{aver} = R_e^W(\kappa)$ for a layer perpendicular to the loading line ($q = 0$, $\alpha = 0$). Regarding the requirements of, e.g., standards concerning the estimation of K_{IC}, it should be noted that in the layer (W), favourable conditions for passing $K_C \to K_{IC}$ occur when the value of K_W is increased [5a,b]. K_C and K_{IC} are the critical values of stress intensity factors adequate for plane stress and strain.

Obviously, the above also applies to the central part of the layer (W) in which the deformation symmetry in maintained. In principle, the factors $K_I = K_C$ and $K_I = K_{IC}$ forfeit their validity because of the presence of normal and tangential stresses and the asymmetry of deformation. In this instance, it is necessary to find a new criterion that expresses the new function $f(K_1, K_2) = f_{kr}$ in a similar manner to the mechanically heterogeneous system in which the degree of heterogeneity is expressed as elasticity constants.

Conclusion

The results of this study concern the evaluation of mechanical properties of undermatched weld joints under static tension. After formulating a simplified model of undermatched weld joints, an analysis was made of stresses for the cases of perpendicular and non-perpendicular orientation of the zone of reduced-hardness (soft-layer) relative to the load action direction. The following revealed features of undermatched weld joints were established:

– The state of stress in undermatched weld joints under static tension;

– The average strength $\sigma_{aver} = f(R_e^W, q, \kappa)$ of undermatched weld joints;

– The parameter $K_W = \sigma_{aver} / R_e^W$ that described change of mechanical properties of undermatched weld joints, Fig. 5;
– The relative thickness $\kappa_{cr} = f(K_s, \gamma^T, q)$ of the layer (W), which has no negative effect of the strength at static tension.

Conditions for producing brittle and ductile fracture in undermatched weld joints in relation to geometrical conditions of the layer (W), expressed by κ, and the mechanical properties of the layer materials, R_e^W, R_0, and equivalent stresses σ_H, σ_v are established in further experiments.

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a. Part I. Characteristic of the constraint effect from microscopic and macroscopic point of view in welded joints. pp. 157–173,
b. Part II. Influence of the constraint effect on the strength and fracture toughness. pp. 175–185.

Reviewer:
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Analiza własności mechanicznych niejednorodnych połączeń spawanych

Słowa kluczowe

Rozkład naprężeń, współczynnik intensywności naprężeń K_{IC}, współczynnik więzów K_W.

Streszczenie

Dostępna techniczna wiedza literaturowa nie potrafi aktualnie dać właściwego opisu relacji pomiędzy ciągliwością i własnościami mechanicznymi, charakteryzującymi spoinę oraz wykonawcze charakterystyki połączeń spawanych.

Po określeniu modelu odzwierciedlającym sytuację w niejednorodnych połączeniach, przedstawiono charakterystykę stanu naprężenia w obszarze różnych stref złącza-spoiny i strefy wpływu ciepła. Wychodząc z powyższej analizy ustalono nowy parametr K_W, charakteryzujący wpływ występujących więzów mechanicznych w niejednorodnej strukturze, który w dalszej kolejności zostanie użyty do oceny mechanicznych własności połączeń spawanych, również z użyciem parametrów mechaniki pękania.