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CHARACTERISTIC OF THE MAIN COMPUTIONAL STEP IN THE ESTIMATE OF WELDABILITY

ABSTRACT

The algorithm for the weldability estimate was presented. In details were presented review of the mathematical relations that define the temperature – dependent space dimensioning in welds and influence of mechanical parameters. Later a brief outline of the metallurgical and micro-structural transformation was presented. Finally, the basic information on strains, stresses and normalised fracture mechanics parameters are characterised.

Key words: *weldability, welded joints, calculation algorithm, numerical analysis, microstructure*

INTRODUCTION

Presently the micro-structural models are in many cases sufficiently advanced to give accurate predictions for welds. Till now the potential of quantitative weldability analysis and method in the design process is not so clear. Just the weldability is mainly conventionally determined and more developed by experimental testing. It is now necessary to focus attention on the relationship between microstructure and mechanical properties, so that data useful as design parameters can easily be generated. The result of this operation is the different step of the susceptibility of material on welding process which physical measure is the fracture resistance of the welded joints. The numerical analysis of weldability has a wide potential to support industrial development projects in future. The potential exist for metallurgists, technologist and design engineers.

THE GLOBAL ESTIMATE OF THE WELDABILITY PROCESS

The mathematical modelling of property – determining processes presents a modern and powerful tool to improve engineering materials and their processing such as welding process. Outgoing from the fundamental mechanisms and their physical representation in the form of equation systems, the effect of influencing factors on weldability can be simulated by numerical models. The application of this method results in a considerable reduction of the total development time and costs of experimental investigation. Beside, the mathematical modelling allows an optimisation of the numerous influencing parameters with the aim to increase the process reliability and to improve the welding construction properties. That means that the modelling of welding processes requires to take into account physical phenomena (thermic, metallurgy and mechanics) and their interactions. The analysis of the welding process from above point of view [1], enable to execute the algorithm which is presented in Fig. 1. The first step of our calculation (module I) effects on the character of heat flow in welding process and determines the nature of the weld thermal cycle and hence, in transformable alloys the metallurgical process and the microstructure of weld metal and heat affected zones (HAZ) (module II) and change of the mechanical specificity (module III). Besides, in agreement with Fig. 1 the estimate of the weldability consists with two stages:

- recurring projection process of the structure feature of weld metal and HAZ in comparison with base metal-submodules 1, 2, 3, 4,
- estimate of the result of this process through analysis of the feature of mechanical properties-submodules 5, 6, 7, 8.

Assessment of the step susceptibility of the base material on welding process is finally lean upon the fracture toughness parameter K_{mat} in terms of stress intensity factor K or his normalised value or others fracture parameters such as J, CTOD, G.

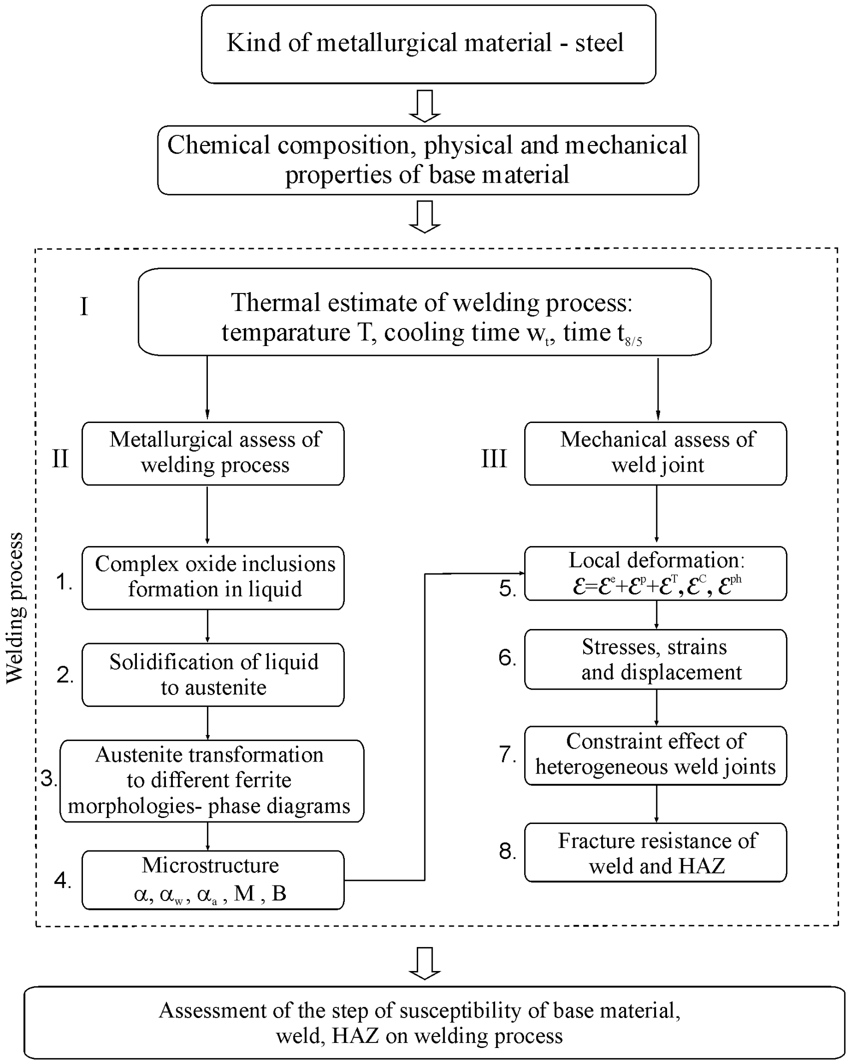

***Fig. 1.** Flow chart of the model to assess numerical weldability.*

THERMAL ANALYSIS OF WELDING PROCESS

The conservation of energy is the fundamental principle in thermal analysis in welding process. Three laws govern mass and heat flow:

- conservation of mass,
- conservation of momentum,
- conservation of energy.

The conservation of mass is expressed by the equation of continuity which, for steady incompressible flow, is [2]:

$$\operatorname{div}\overline{v} = 0 \tag{1}$$

where: v – velocity of the fluid.

The conservation of momentum is expressed by:

$$\rho\frac{dv}{dt} = -\nabla p + \eta\nabla^2 v + \overline{J}\cdot\overline{B} + \rho\cdot g \tag{2}$$

where:

ρ - mass density,
∇p - pressure gradient,
η - viscosity,
$\overline{J}x\overline{B}$ - the Lorenz force,
J - current density,
B - magnetic flux density,
g - acceleration due to gravity.

The conservation of energy is expressed by energy equation:

$$\rho c_p\frac{\partial T}{\partial t} = \lambda\nabla^2 T - \rho c_p(\overline{v}\cdot\nabla)T - \operatorname{div}\overline{q}_r + \frac{J^2}{\sigma_e} + \phi \tag{3}$$

where:

c_p - specific heat at constant pressure,
t - time,
T - temperature,
λ - thermal conductivity,
q_r - radiation energy,
σ_e - electrical conductivity,
ϕ - viscous dissipation of energy.

If we ignore the last three terms on the right-hand side of eq. (3), which represent radiation, Joule heating and viscous energy dissipation respectively, and assume steady conditions of welding process $(\partial T/\partial t = 0)$, we obtain:

$$\lambda\nabla^2 T - \rho c_p(\overline{v}\cdot\nabla)T = 0 \tag{4}$$

where:

$$(\overline{v}\cdot\nabla)T = v_x\frac{\partial T}{\partial x} + v_y\frac{\partial T}{\partial y} + v_z\frac{\partial T}{\partial z} \tag{5}$$

The first term in eq. (4) represent the rate of heat loss by conduction and the second the rate of heat loss by convection.
Finally, the eq. (4) is the governing equation for heat flow in all welding processes that employ a moving source of heat.
The equation (1) ÷ (5) has fundamental meaning at estimate of module I. The problem of assessment module II and submodules 1÷4 are analysed and presented previously [1].

MECHANICAL ANALYSIS OF WELD JOINT

The mechanical analysis of the welded joints is more complex then the heat flow analysis because of the geometry changes and because of the complex stress – strain relationship. In designing a welding procedure, the critical issues are defects, mechanical properties, distortion, residual stress and heterogeneous structure. Models of the mechanical properties of base metal, HAZ and weld metal, are needed as input data for thermal analysis. The welding process has dynamic character and in general, mechanical behaviour of metals under thermal cycle can be described by module III and submodules 5 ÷ 8, Fig.1. In this conceptual modelling, the constitutive relation: stress-strain link is the most important in the welding mechanics. One of the fundamental assumption is that the total strain can be divided into components which are produced by different physical processes – module 5. Since, the thermal strain disappears when the temperature returns to the ambient temperature after the thermal cycle.
In this situation the elastic strain ε^e is produced by the residual stress and the total strain ε correspond to the residual deformation. It is seen, conceptually, that the residual stress and the residual deformation are produced by the inherent strain ε^{inh} [3]:

$$\varepsilon^{inh} = \varepsilon^{p} + \varepsilon^{c} + \varepsilon^{ph} = \varepsilon - \varepsilon^{e} \tag{6}$$

where:

ε - total strain,
ε^e - elastic strain,
ε^p - plastic strain,
ε^{ph} - phase transformation strain,
ε^{inh} - inherent strain.

In similar manner this problem has been defined by Okerbłom [4]. The coupling between thermal and mechanical fields enable to assess the thermo-mechanical diffusion equation [5]:

$$\rho c \dot{T} + \partial q_i / \partial x_j = \dot{Q}_{int} - \frac{E \alpha T}{1 - 2\nu} \cdot \dot{\varepsilon}^{e}_{ii} + \xi S_{ij} \dot{d}_{ij} \tag{7}$$

where:

q_i - heat flux per unit area,
Q_{int} - internal heat generation,
S_{ij} - deviatoric stress tensor,
d_{ij} - viscoplastic strain rate tensor,
ξ - parameter characterising inelastic energy dissipation $S_{ij}\dot{d}_{ij}$ ($\xi<1$).

Therefore it is possible to divide the thermo-mechanical analysis of the welding process into two main parts – the analysis of the thermal field and the subsequent analysis of the mechanical fields for estimate residual stresses and residual deformation submodule 6.

The submodule 7 characterises the influence of constraint effect of heterogeneous welded joints on the mechanical properties. The effect of strength mis-match in steel weldments has received much attention.

The constraint effect in the heterogeneous microstructure of materials and mismatched welded joints, called heterogeneous systems, also depends on physical phenomena at the interface of zones with different mechanical properties and their geometric configuration and on local stress.

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) which is taken into account and presented in Fig. 2.

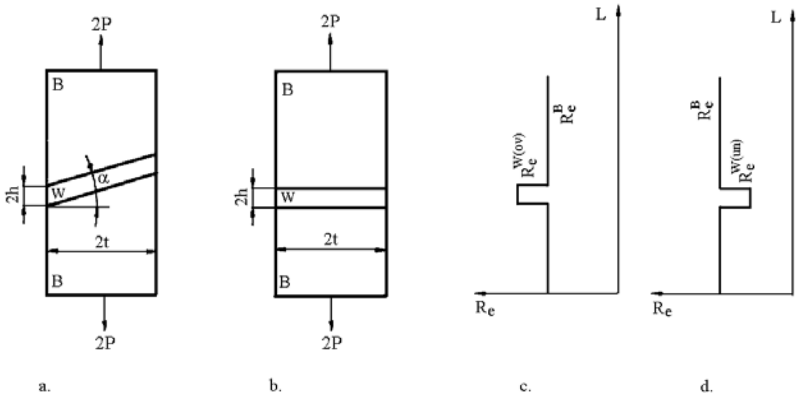

Fig. 2. Characteristics of the models of mismatched welded joints: a. geometrical configuration - layer W is inclined to external load, b. geometrical configuration - layer W is perpendicular to external load, c. change of the yield point R_e in the overmatched weld joint, d. change of the yield point R_e in the undermatched weld joint.

The macro-mechanical heterogeneity of welded structures is one of their primary features. The heterogeneous nature of the weld joints is characterised by macroscopic dissimilarity in mechanical properties. This mismatch causes constraints in macroscopic scale and local 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 local change in the stress occurring at the interface of zones (B) and (W) is then of primary importance for correct interpretation and estimation of new mechanical properties. The stress analysis in this area has been performed previously [6].

Furthermore the analysis of change of stress state in mismatched models of welded joints enables estimating the constraint factors as follows [7]:

$$K_W^{un} = \frac{2}{\sqrt{3}}\left(\frac{1}{4(1-q)}\left[\frac{\pi}{2} + 2(1-2q)\sqrt{q(1-q)} - \arcsin(2q-1)\right] + (1-q)\frac{1}{4\kappa}\right) \tag{8}$$

$$K_W^{ov} = \frac{2}{\sqrt{3}}\left(\frac{1}{4(1-q)}\left[-\frac{\pi}{2} - 2(1-2q)\sqrt{q(1-q)} + \arcsin(2q-1)\right] + (1-q)\frac{1}{4\kappa}\right) \tag{9}$$

where: $0 \leq q < 1$ and $\kappa = 2h/2t$.

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

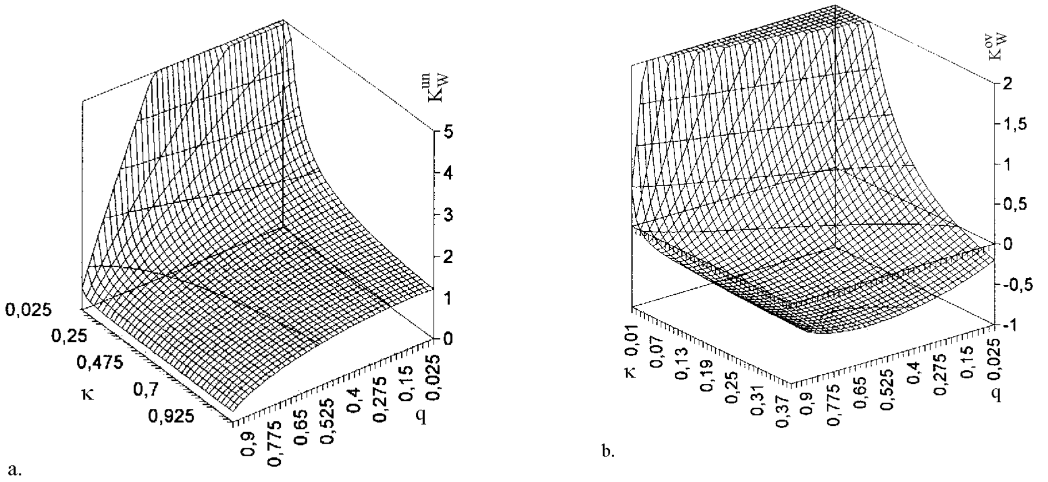

Fig. 3. Diagrams of K_W^{un}, K_W^{ov} for: (a) undermatched; (b) overmatched models of weld joints.

Furthermore some values of $K_W^{un/ov}$ are presented in Tab.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 above data indicate that the constraint factors K_W^{un}, K_W^{ov} increase at small values of κ and q but attain different values for under- and overmatched cases. Under the assumption that the materials of zones B and W are perfectly ductile the new values of the yield point is given by:

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

$$R_e^{W(un)} = K_W^{un} \cdot R_e^W \tag{10}$$

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

$$R_e^{W(ov)} = K_W^{ov} \cdot R_e^W \tag{11}$$

The values of $K_W^{un/ov}$ indicate that the constraint effect considerably influences the mechanical properties of the mismatched weld joints. This can be expressed by the average values of stresses that can be transferred by a joint with a soft or hard layer as [7]:

$$\sigma_{ever}^{un}=\frac{2R_e^{W(un)}}{\sqrt{3}}\left\{\frac{1}{4(1-q)}\left[\frac{\pi}{2}+2(1-2q)\sqrt{\{q(1-q)\}}-\arcsin(2q-1)\right]+(1-q)\frac{1}{4\kappa}\right\} \quad (12)$$

$$\sigma_{ever}^{ov}=\frac{2R_e^{W(ov)}}{\sqrt{3}}\left\{\frac{1}{4(1-q)}\left[-\frac{\pi}{2}-2(1-2q)\sqrt{q(1-q)}+\arcsin(2q-1)\right]+(1-q)\frac{1}{4\kappa}\right\} \quad (13)$$

where:

$R_{ever}^{W(un)}, R_{ever}^{W(ov)}$ - tensile yield point of the layer (W) for under- and overmatched case,

q - factor which charactering the influence of normalised tangential stresses at the interface, $0 \le q < 1$.

If $q = 0$ ($\alpha = 0$), equation (16) assumes the form determined by Kačanov [8] for the undermatched case. The theoretical values of K_W^{un} indicate that mechanical properties of the so-called soft layer can be considerably improved due to the change in stresses of that area. If the mechanical properties of the material in the zone (B), determined as R_m^B (tensile strength) and R_e^B (tensile yield strength), correspond to mechanical properties of the material in its initial state before welding, and $\sigma_{ever} = R_m^B$, then the relative thickness of layer (W) κ_{cr} which has no negative effect on the strength of the welded joint can be calculated from the following equation:

$$K_s = R_e^B / R_e^{W(un)}, \quad \gamma^B = R_m^B / R_e^B$$

$$\kappa_{cr}=\frac{1-q}{2\sqrt{3}(1-q)K_s\cdot\gamma^B-\left[\pi/2+2(1-2q)\sqrt{q(1-q)}-\arcsin(2q-1)\right]} \quad (14)$$

A change in state of stress in the heterogeneous system leads also to a change in fracture resistance in these zones and the mode of fracture what is characterised by submodule 8. For example let's consider the above - mentioned problem when the crack is located in the middle part of the layer parallel to the interfaces and material is homogeneous. One of the most important procedures is the recently introduced Engineering Treatment Model (ETM) which permits to use the CTOD as functions of the applied load or strain for work hardened materials.

In accordance with the ETM for assessing the ratio of the driving forces in mismatching model and after taking the constraint factor $K_W^{un/ov}$, it will be able to determine the normalised parameter $\delta_R = \delta_W / \delta_B$ (δ_W, δ_B - the CTOD of crack in the weld metal (W) and base metal (B) respectively) as follows [9, 10]:

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

$$\sigma_1 \geq R_e^B \geq R_e^{W(un)} \qquad \delta_R = \left(\frac{K_W^{un}}{K_S}\right)^{\left(\frac{1}{n_W} - \frac{1}{n_B}\right)} \left(\frac{1}{K_S}\right)^{\left(1 - \frac{1}{n_W}\right)} \tag{15}$$

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

$$\sigma_1 \geq R_e^{W(ov)} \geq R_e^B \qquad \delta_R = \left(\frac{K_W^{ov}}{K_S}\right)^{\left(\frac{1}{n_W} - \frac{1}{n_B}\right)} \left(\frac{1}{K_S}\right)^{\left(1 - \frac{1}{n_W}\right)} \tag{16}$$

where:

n_W, n_B - strain hardening exponents for materials of regions (W) and (B) respectively – Fig. 2.

The results of this study of mismatched weld joints reveals high dependence of the fracture parameter δ_R according to equations (15÷16) on parameters such as $K_W^{un/ov}$, K_S and n_W, n_B. These are new and modified equations in which was introduced the quantitative assessment of the constraint effect on the fracture toughness of the mismatched weld joints is used. For example on Figs 4 and 5 are presented the characteristics of the driving forces ratio δ_R as a function of relative thickness κ of zone W in according to equations (15, 16) for a ferritic steel.

- undermatching case

$R_e^W = 434$ MPa ; $R_e^B = 605$ MPa
$n_W = 0{,}25$; $n_B = 0{,}20$

- overmatching case

$R_e^W = 605$ MPa ; $R_e^B = 434$ MPa
$n_W = 0{,}20$; $n_B = 0{,}25$

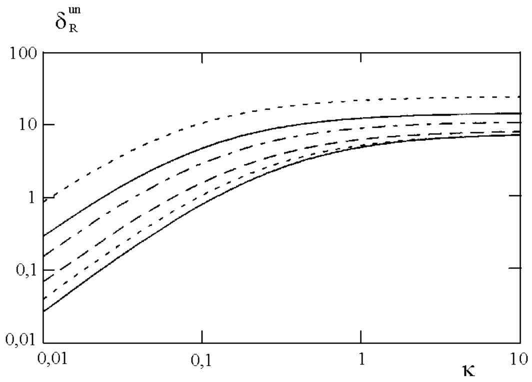

Fig. 4. Diagram of δ_R^{un} as a function of κ at q = 0,1 ÷ 0,9 and K_S = 1,39.

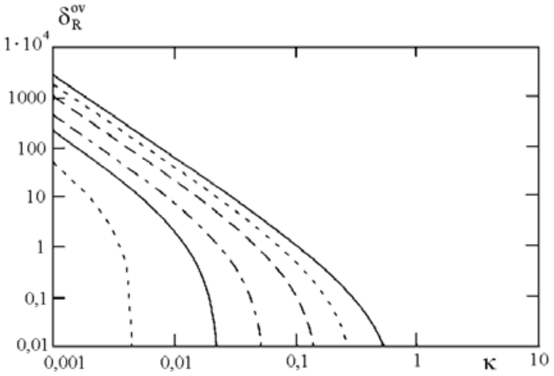

Fig. 5. Diagram of δ_R^{ov} as a function of κ at q = 0,1 ÷ 0,9 and K_S = 0,72.

The results of this study of mismatched weld joint reveals high dependence of the fracture parameter δ_R according to equations (15÷16) on the constraint factors K_W^{un}, K_W^{ov} and matching ratio K_S and strain hardening exponents n_W, n_B.

According to former configuration the following revealed features of under- and overmatched weld joints were established:

- quantitative assessment of constraint effect by introducing the constraint factors K_W^{un} and K_W^{ov},
- the constraint factors depend on the physical (q) and geometrical (κ) parameters,
- relative thickness $\kappa_{cr} = f\left(K_S, \gamma^B, q\right)$ of the zone (W) for undermatched weld joints which has no negative effect on the strength at static tension,
- a condition for producing brittle or ductile fracture in mismatched weld joints.

Furthermore an analytical assessment of the fracture resistance of an undermatched and overmatched welded joints reveals dependence of driving forces ratio δ_R according to equations (15÷16) on parameters such as constraint factors, K_W^{un}, K_W^{ov}, matching ratio K_s and strain hardening exponents n_W, n_B.

ASSESSMENT OF THE STEP OF SUSCEPTABILITY OF WELDED JOINTS ON WELDING PROCESS

The final question is assessment of the step of susceptibility $S_{m/w}$ of welded joints on welding process. In accordance with PN-84/M-69005 the physical measure of this phenomena we can accept the fracture resistance of welded joints mainly characterised by fracture mechanics parameter.

Fracture mechanics design methodology is based on the realistic assumption that all materials contain initial defects that affect the load-carrying capacity of engineering structures. Defects are initiated in the material by manufacturing procedures or can be created during the service life, like fatigue, environment-assisted or creep cracks. Usually, one dominant crack is assumed. Two pieces of information are needed to make a prediction of the failure behaviour in structural components containing defects such as cracks. They are the deformation behaviour of the structure and the fracture behaviour. The deformation behaviour gives the relationship between load and displacement of the component or an analogous relationship such as stress and strain. It is usually done independently of the fracture behaviour but is done with the inclusion of the effect of the defect. Deformation behaviour usually combines a linear-elastic and an elastic-plastic contribution. The fracture parameters are also determined from the deformation behaviour of the structure and would include a combination of a linear elastic term, usually (SIF) – $K_,$ based and an (CTOD) - δ. The deformation behaviour usually requires a knowledge of the tensile properties of the material in the structure.

A fracture safe design can be also influenced by constraint effect specially in weld structures. Current work has concentrated more on looking at constraint effects on the fracture behaviour. Concern must also be given to the effect of constraint on deformation behaviour, especially in the nonlinear region of behaviour. The nonlinear local deformation take place in mismatched weld joints of the structures. The Engineering Treatment Model (ETM) applied to an analysis of mismatched weld joint uses calibration functions in which load is normalised by limit load and toughness.

Recently the (ETM) was modified by introducing the constraint factor for under- and overmatched weld joints.

In agreement with above statement the normalised parameter $\delta_R = \delta_W / \delta_B$ (δ_W, δ_B - the CTOD of crack in the weld metal (W) and base metal (B) respectively) can be used to assessment the step of susceptibility of the base material on welding process as:

$$\delta_R = S_{m/w} \geq 1 \tag{17}$$

where: δ_R is described by eqs. (15), (16). The determined normalised parameter δ_R gives the basic information about how in simplified way to choose the critical parameter CTOD in mismatched welded joints for strength equal to base metal and good weldability.

CONCLUSION

Being based on the couple thermo-mechanical interaction in welding process there define the algorithm for the weldability estimate with the modules I÷III and submodules 1÷8 for the numerical assessment of this one. It analysed mainly the thermo-mechanical modules I÷III and submodules 5÷8 because of [1]. The basic characteristic of strains, stress, constraint effect and normalised fracture mechanics parameters as measure of the susceptibility are presented. Finally, an analytical assessment of the step of susceptibility of base material, weld, HAZ on welding process is described.

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