The Effect of Mechanical Heterogeneity on Finite Element Numerical Evaluation of J-integral for Cracked Weld Joints

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Abstract. In this paper the effect of random mechanical properties of the welded joint on the value of J-integral is studied by finite-element modeling. The results show that with increasing of the yield stress distribution range the J-integral value is also increasing which requires adjustments to calculations of J-integral for structurally heterogeneous materials.

Introduction

Evaluation of the stress-strain state of welded joints with crack-like defects is one of the most challenging problems in fracture mechanics. The residual welding stresses and mechanical heterogeneity can lead to complex deformation patterns in the cracked area [1]. Typically, the deformation is strongly nonlinear and requires using relevant criteria to assess fracture due to such defects [2].

The nonlinear effects in heterogeneous welded joints are generally studied as "soft" and "hard" layers [3, 4] using the methods of finite-element modeling (FEM) [5-8]. But a special interest is to examine the effect of microstructural heterogeneity on fracture of welds [9, 10], as the mechanical properties of a welded joint are continuously changing from one zone to another with some random variation [11]. Accordingly, a finite element model of heterogeneous welded plate is proposed.

Model

The two-dimensional welded plate under plane stress axial tension contains three zones – the base metal, weld metal and heat-affected zone (HAZ). The crack is located between the weld metal and HAZ (Fig. 1). The yield strength follows the normal distribution with certain parameters for each zone (Table 1) and its value is specified for finite elements at random.

Table 1. The distribution parameters of the yield strength

Weld zone	**Mean [MPa]**	**Coefficient of variation**
Base metal	338	0.05
HAZ	313	0.07
Weld metal	511	0.12

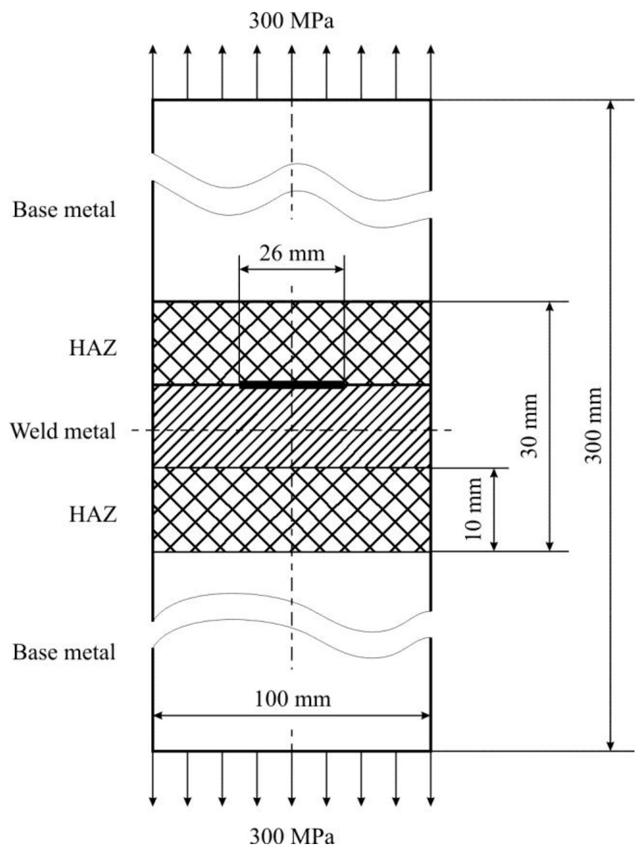

Fig. 1. The model of a welded plate

Elastic properties are constant for all zones with the Young's Modulus, $E = 2.1\text{x}10^5$ MPa and Poisson's ratio, $\nu = 0.3$. The elasto-plastic behavior is described by power law

$$\begin{cases} \sigma = E\varepsilon \text{ if } \varepsilon \le \varepsilon_{\text{т}}; \\ \sigma = \sigma_{\text{т}}\left(\dfrac{\varepsilon}{\varepsilon_{\text{т}}}\right)^m \text{ if } \varepsilon > \varepsilon_{\text{т}} \end{cases} \tag{1}$$

where $\sigma_{\text{т}}$, $\varepsilon_{\text{т}}$ are yield strength and strain respectively, $m = 0.12$.
The problem is solved with the ANSYS code using APDL macro [12, 13]. The J-integral is given by

$$J = \int_{\Gamma}\left(Wn_1 - \sigma_{ij}n_j\frac{\partial u_i}{\partial x_1}\right)ds \tag{2}$$

where Γ is an anti-clockwise path, W is the strain energy density, defined as

$$W = W(\varepsilon_{ij}) = \int_0^{\varepsilon_{ij}} \sigma_{ij}d\varepsilon_{ij}\ , \tag{3}$$

σ_{ij} ε_{ij}, u_i are the stress, strain and displacement respectively, n_i is the outward normal to Γ.

Simulation

At first, the model is studied without taking the heterogeneity into account, i.e. the yield strength is constant for each zone of the welded joint. In the second case, the yield strength is assigned for each finite element at random (Fig. 2). The J-integral is calculated by averaging its value over a set of paths. To study the effect of yield strength distribution range on the J-integral, the simulation is repeated several times (Table 2).

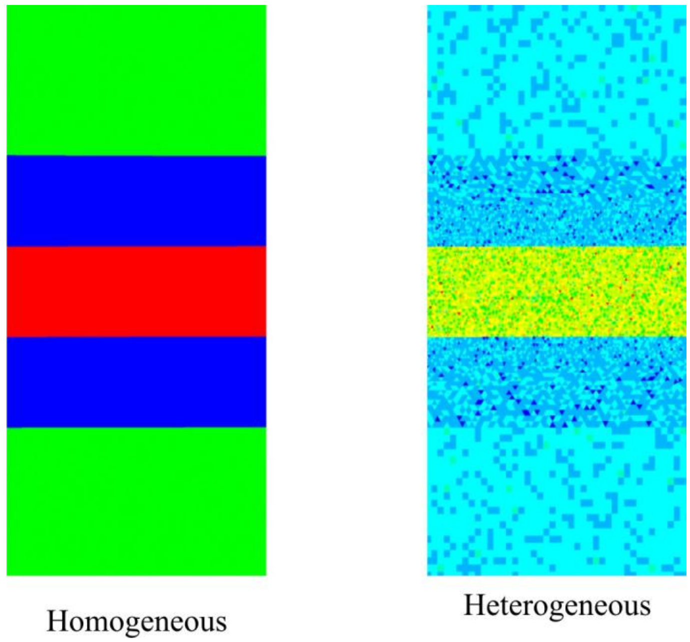

Fig. 2. The yield strength distribution in the finite element model

Table 2. The yield strength distribution range and the mean J-integral value

Simulation case number	**Yield strength range, [MPa]**			**Mean J-integral value, [kJ/m^2]**
	Weld metal	**HAZ**	**Base metal**	
1	338	313	511	50,80
2	321,0 – 355,0	297,4 – 328,7	485,5 – 536,6	51,06
3	304,2 – 371,8	281,7 – 344,3	459,9 – 562,1	51,62
4	287,3 – 388,7	266,1 – 360,0	434,4 – 587,7	52,59
5	270,4 – 405,6	250,4 – 375,6	408,8 – 613,2	52,81
6	253,5 – 422,5	234,8 – 391,3	383,3 – 638,8	53,11

Summary

The results obtained display that with increasing the yield strength range the J-integral value is also increased as it is shown in Fig. 3. Such dependence can be explained by the larger amount of elements enduring a high plastic deformation. The study shows that stochastic nature of mechanical properties should be taken into account in calculation of J-integral for structurally heterogeneous materials. Further research on the refinement of the model and its verification with experimental data are needed.

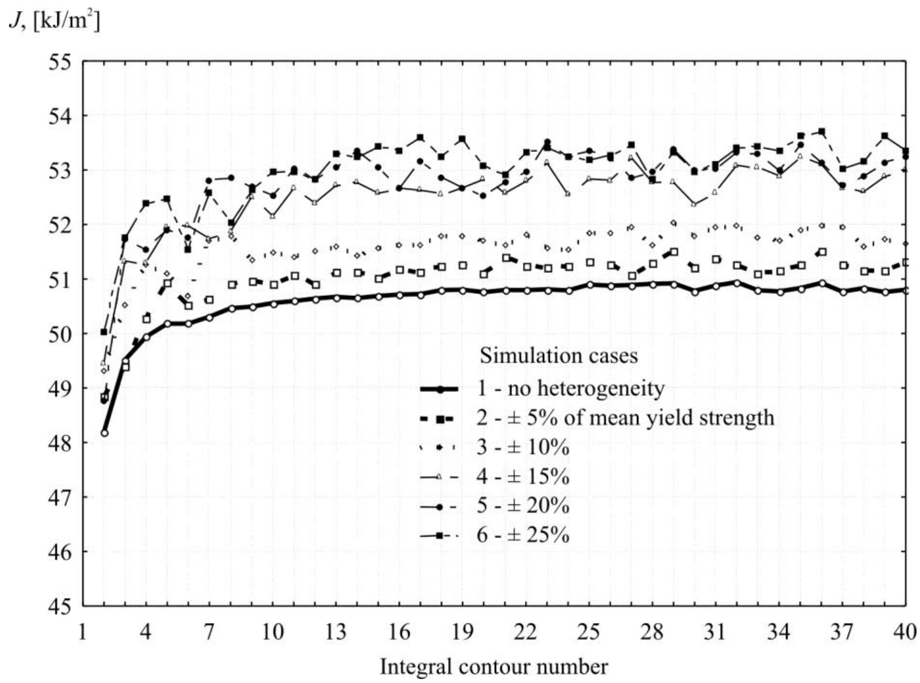

Fig. 3. The effect of random yield strength range on the J-integral

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