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APPLICATION OF SIMPLIFIED MECHANICAL MODEL FOR DESCRIPTION OF SPECIMEN SIZE EFFECT ON RESISTANCE AGAINST STABLE TEARING

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Abstract: *This contribution deals with a size effect on J-R curve of three points bend specimens made from Eurofer97 steel and with possibilities to predict the specimen behaviour between various specimen sizes. To do it, a simplified mechanical model proposed by Schindler is applied to obtained tests results in order to predict observed size effect on J-R curve.*

Keywords: Size effect, Three point bend, Scaling laws, Eurofer97, J-R curve.

1. Introduction

The fracture toughness standards specify the size requirements on tested specimens in order to maintain a validity of fracture parameters describing the conditions at the crack tip in relation to measured toughness values (ISO 12135, 2002). These size requirements are is cases of materials with high toughness very demanding concerning the size of tested specimens. Moreover there are certain cases where is available only limited amount of test material and only miniature specimens offer possibilities of direct fracture toughness estimation. In both cases an interpretation of measured values in relation to valid values of fracture parameters or for application to structural components is needed (Dlouhý et al., 2006). The studied material Eurofer97 steel was developed for applications in nuclear industry. The specimen size effect in these applications is very relevant especially when miniature specimens demonstrate significant decreasing of resistance against stable tearing for high toughness alloys (Ono et al., 2006). In following, the Schindler's model (Schindler and Veidt, 1998) is briefly introduced and it is applied to the experimentally determined results to predict specimen size effect on J-R curve of the Eurofer97 steel.

2. Schindler's Model

As shown by the Schindler et al. (Schindler and Veidt, 1998; Schindler and Bertschinger, 2002) the J-R curve (Fig. 1) can be estimated from the continuous force-displacement diagram of a single, uninterrupted, static or dynamic bending test (Fig. 2) by:

$$J(\Delta a) = C \cdot \Delta a^{p} \text{ for } \Delta a = \Delta a_m , \tag{1}$$

where

$$C = \left(\frac{2}{p}\right)^{p} \cdot \frac{\eta(a_0)}{B\,(W - a_0)^{1+p}} \cdot W_t^{\ p} \cdot W_{mp}^{\ 1-p} , \tag{2}$$

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$$p = \left(1 + \frac{W_{mp}}{2W_t}\right)^{-1}. \qquad (3)$$

B and $b_0 = W - a_0$ are the specimen thickness, and ligament length, respectively. Δa_m is a crack length at maximum force (F_m), Fig. 1. W_{mp} and W_t are dissipated energy at maximum force and the total fracture energy, respectively. These values of energies can be obtained from the load-displacement diagram (Fig. 2). W_{mt} is a remaining part of the total fracture energy consumed for a breaking of specimen. Mutual relation between mentioned characteristic energies is given in (4).

$$W_t = W_{mp} + W_{mt}. \qquad (4)$$

According to eqs. (1-3) the J-R curve is determined by only two experimental parameters, W_{mp} and W_t, which can be determined from the force-displacement diagram.

The scaling laws for parameters, W_{mp} and W_t, were derived based on the same mechanical models and the same assumptions as used for derivation of eqs. (1-3) (Schindler and Veidt, 1998). In the following, data corresponding to the sub-size specimens or their dimensions are denoted by a prime, i.e. $F_m^{'}$, $W_{mp}^{'}$ or $B^{'}$.

The energy at the maximum force was derived as:

$$W_{mp} = \frac{B}{B^{'}} \cdot \frac{\eta^{'}}{\eta} \cdot \left(\frac{b_0}{b_0^{'}}\right)^{1+p} \cdot W_{mp}^{'}, \qquad (5a)$$

where

$$p = \left(1 + \frac{W_{mp}^{'}}{2W_t^{'}}\right)^{-1}. \qquad (5b)$$

The total fracture energy is given by Eq. (4). Scaling laws for the first term is given in Eq. (5). The second term was obtained in the form:

$$W_{mt} = \frac{B}{B^{'}} \cdot \frac{\eta^{'}}{\eta} \cdot \left(\frac{b_0}{b_0^{'}}\right)^{2} \cdot W_{mt}^{'}. \qquad (6)$$

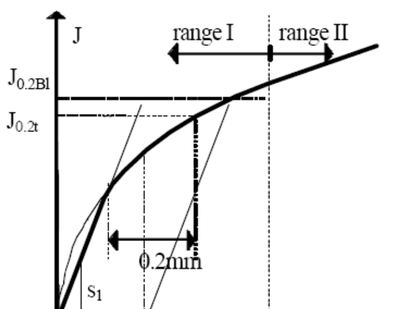


Fig. 1: Schematic description of J-R curve.

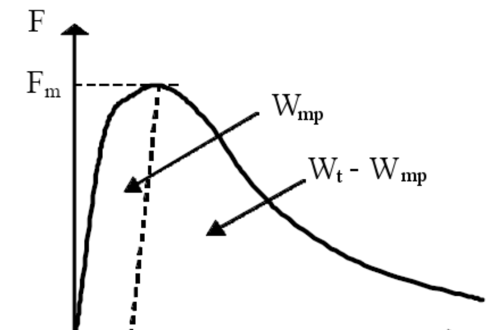
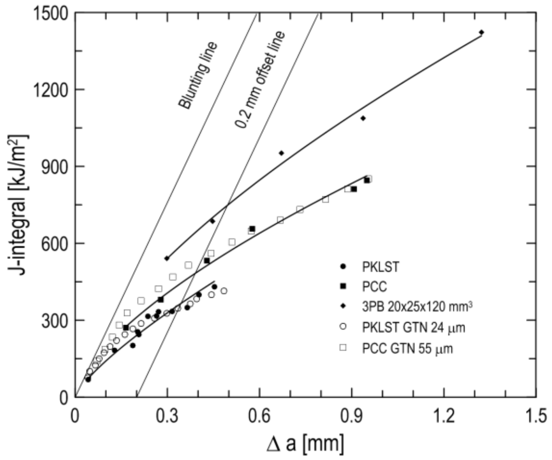


Fig. 2: Load vs. displacement diagram.

3. Description of Realized Experiments

Crack resistance curves were measured to describe specimen size effect in ductile regime of the Eurofer97 steel. The specimens were manufactured from the plate of thickness 25 mm (heat nr. 993393) with crack orientation in transversal direction of the plate. J-R curve were measured on three sizes of pre-cracked three-point-bend specimens (Tab. 1) by multi-specimen technique by test rate 1 mm/min at room temperature. The construction of curves was done in accordance with standard ISO 12135 (ISO 12135, 2002).

The input values to the Schindler's model require description load vs. deflection of specimen loaded up to total fracture. However, results of appropriate experiments have not been available yet. In order to verify the possibilities of prediction of Schindler's model the calibrated damage model of ductile fracture Gurson-Tvergaard-Needleman (Tvergaard and Needleman, 1984) was used to obtain load vs. deflection diagram of selected specimens PKLST and PCC. In previous work this damage model was calibrated for studied steel (Stratil et al., 2013) and the J-R curves of tested specimens were successfully simulated provided an appropriate element size is chosen (Stratil, 2014). Due to good description of J-R curves, see Fig. 3, it is assumed that GTN model provides a reliable simulation of the total fracture of the specimens. The outputs from performed three dimensional simulations of the tests of PKLST and PCC specimens with the element size from Fig. 3 are in Fig. 4 and the obtained key parameters are in Tab. 1.



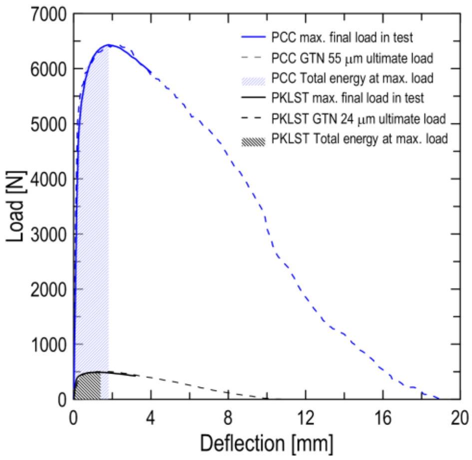


Fig. 3: Experimentally measured J-R curves and results of GTN model simulation (left).

Fig. 4: Load vs. displacement diagram obtained from simulations of PCC and PKLST (right).

Tab. 1: Parameters from simulation of tests by GTN model and specimen characteristics.

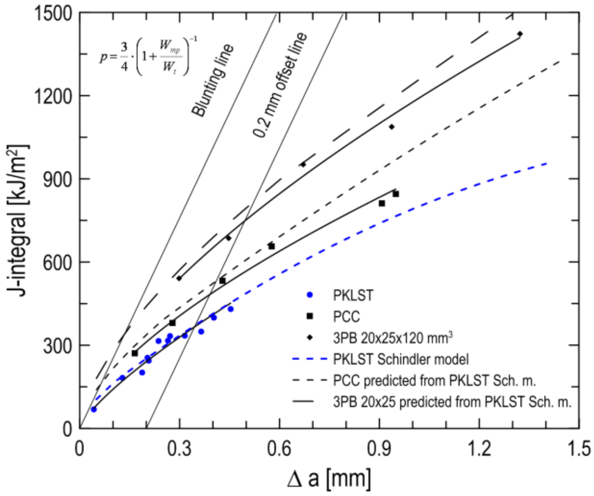
Key parameter	**PKLST**	**PCC**	**Dimensions**	**PKLST**	**PCC**	**3PB 20×25**
W_{mp} [J]	0.508	9.506	B [mm]	3	10	20
W_t [J]	2.945	26.726	W [mm]	4	10	25
F_m [kN]	0.502	6.449	b_0 [mm]	2	5	11.9
			S [mm]	24	40	100

4. Application and Discussion of Schindler's Model

The experimental results of J-R curve measurement showed a very strong size effects. Decreasing of specimen size leads to decrease both initiation and propagation values of J-integral. In case of pre-cracked specimens Schindler recommends using a modified definition of power law exponent p for suitable approximation of real shape of J-R curve (Schindler and Veidt, 1998):

$$p = \frac{3}{4} \cdot \left(1 + \frac{W_{mp}}{W_t}\right)^{-1} . \tag{7}$$

A optimised procedure for prediction of J-R curve of specimen of different size is hence following. First, the key test parameters of the measured specimen are scaled-up/down to a desirable specimen size and then construction of J-R curve of desirable specimen size is carried out using a modified definition of power law exponent. Predicted J-R curve both from key test parameters of PKLST and PCC specimens are in Fig. 5 and 6. With regard to the simplification of the model, natural scatter of measured data and the use of input data from simulations of GTN model are predicted curves in close agreement with experimental data.



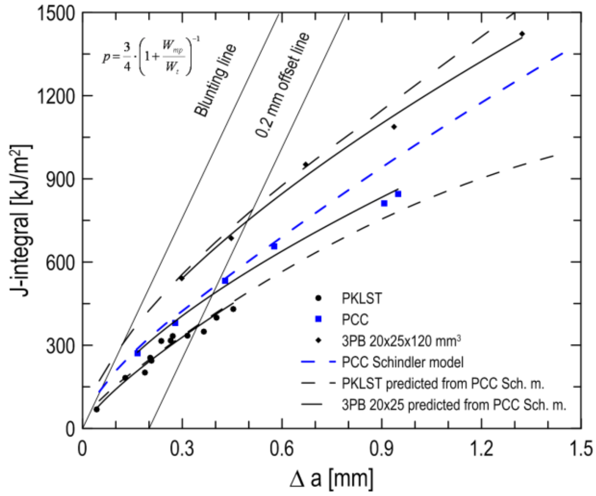


Fig. 5: Experimental J-R curves and their prediction by Schindler's model based on data of PKLST (left).

Fig. 6: Experimental J-R curves and their prediction by Schindler's model based on data of PCC (right).

5. Conclusions

The performance of Schindler's model seems to be very promising for prediction of specimen size effect on J-R curves or potentially for other fracture characteristics. For suitable application of the model to a pre-cracked specimen a modified definition of power law exponent is needed. The results of this study were based on the outputs from FE simulations of total specimens' fracture using calibrated GTN model. It is necessarily to verify obtained findings using real experimental data, what will be done in future.

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