Temperature Dependence of Beremin-model Parameters for RPV Steel

Gyöngyvér B. Lenkey[1], Róbert Beleznai[1]

[1] Bay Zoltán Foundation for Applied Research, Institute for Logistics and Production Systems, 3519 Miskolc, Iglói u. 2. Hungary
lenkey@bzlogi.hu, beleznai@bzlogi.hu

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Abstract. The objective of the present work was to investigate the effect of material properties, i.e. yield strength and strain hardening exponent on the Beremin-model parameter for ASTM A533 grade B class 1. Using the master curve approach, temperature dependence of σ_u has also been determined.

Introduction

The brittle fracture resistance of the materials can be described by statistical methods. Nowadays the micromechanical modelling of the fracture behaviour is widely applied and studied, when size, geometry and temperature dependent material parameters can be determined. The original Beremin-model [1] uses two parameters for describing the fracture process connecting the microscopic defects and the stress state with the fracture probability. In the present study the model parameters were determined using the master curve approach: it was assumed that the failure probability at median J value (J_{med}) is 50 %, i.e.

$$P_f = 0.5 = 1 - \exp\left[-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right] \tag{1}$$

where m is the Weibull modulus, and σ_u the scale parameter of the shape of the Weibull distribution. σ_w is the Weibull stress calculated by integrating over a defined fracture process zone:

$$\sigma_w = \left[\frac{1}{V_0}\int_V \sigma_1^m dV\right]^{\frac{1}{m}} \tag{2}$$

Where V defines the volume of the process zone, V_o represents the reference volume and σ_1 is the maximum principal stress.

Effect of material properties on Beremin model parameters

JRQ reference RPV un-irradiated material (ASTM A533 grade B class 1) was investigated at different temperature, the fracture tests were performed by AEKI-KFKI on pre-cracked and side-grooved Charpy-type specimens (10x10x55 mm). Fracture toughness data were available at different temperatures between -50 °C and -110 °C (Fig.1.).
For the stress calculation, MSC. MARC 2005 finite element code was used. 2D plain strain model was developed with different crack lengths (according to the real crack sizes) and refined mesh size was applied around the crack tip. The blunted crack radius was 2.5 μm.

It has been shown in [2] that unique parameter combination cannot be determined only form one set of fracture toughness experiments, therefore σ_u was calculated with fixing m=10, which has been found to be temperature independent and valid for low constraint specimens. σ_u was determined from the master curve – based on the condition that at K_{med} the probability of failure is P=0.5 – using eq. (1).

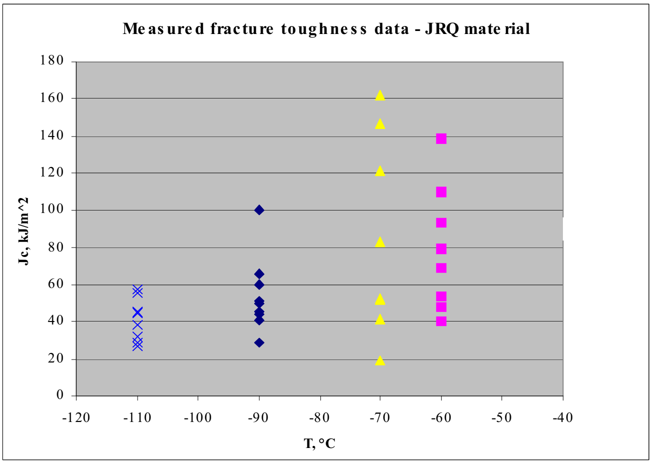


Fig. 1. Fracture toughness data of pre-cracked Charpy-type specimens at different temperatures

First sensitivity analyses have been performed in order to determine the effect of yield strength and hardening exponent variation on the model parameters, using the material data at -70 °C. The yield strength was varied with ±25 MPa relative to the measured one. The strain hardening exponent was varied between 0.1 and 0.25. As it can be seen in Fig.1. the yield strength has appr. linear relationship with the Weibull modulus σ_u (10 % variation in yield strength causes 5% change in σ_u), but the strain hardening exponent variation has larger effect at larger n values. Fig. 2. shows the effect of yield strength and hardening exponent variation on the fracture probability.

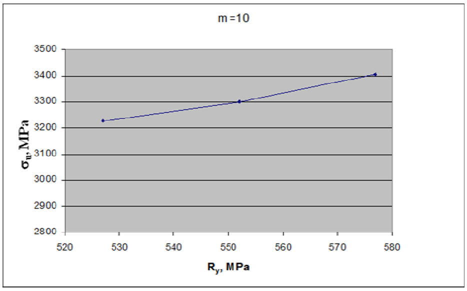
Temperature dependence of σ_u parameter

Master curve [3] describes the temperature dependence of the fracture toughness according to the following equation:

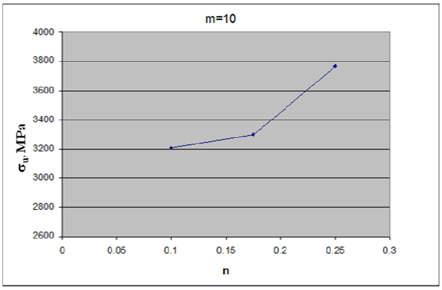
$$K_{1T} = 30 + 70.\exp\{0.019.(T - T_0)\} \tag{3}$$

The T_o reference temperature for the investigated RPV steel was determined according to [2] and was obtained T_o=-76.6 °C.
A procedure has been developed to determine the temperature dependence of σ_u which is described as follows:

- Master curve describes the T dependence of K_{med}, from which $J_{med}(T)$ can be calculated
- On the basis of the FEM calculation: from $\sigma_u(J_{med})$ function (see Fig. 4. and Fig.5.) $\sigma_u(T)$ relationship can be determined for a given material law
- On the basis of the sensitivity analyses for the yield strength (R_y): from σ_u (J_{med}) σ_u (T) relationship can be determined for different material law (Fig. 6.)
- Knowing the temperature dependence of R_y, $\sigma_u(T)$ function can be determined (Fig. 7.).

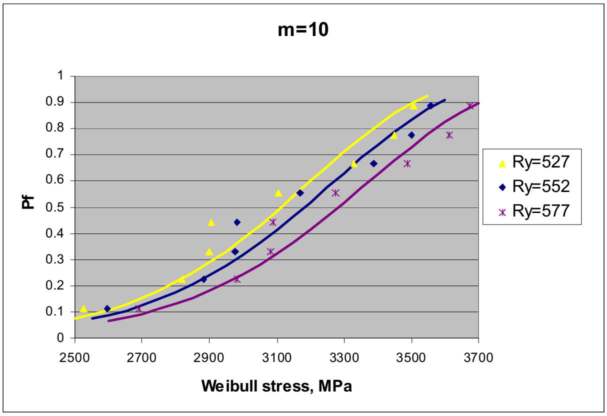


a)



b)

Fig. 2. Effect of the yield strength (a) and the strain hardening exponent (b) on the Beremin model parameter σ_u (m=10)



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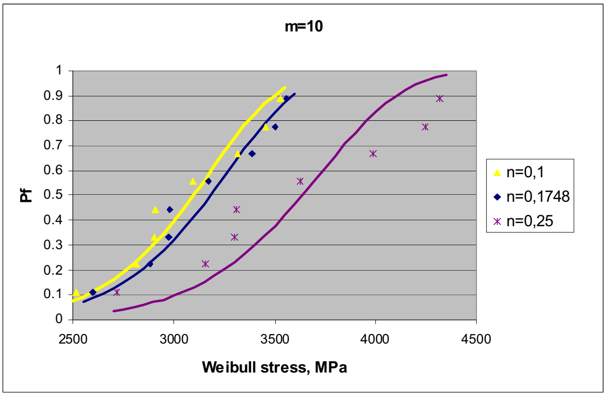

b)

Fig. 3. Effect of the yield strength (a) and the strain hardening exponent (b) on fracture probability

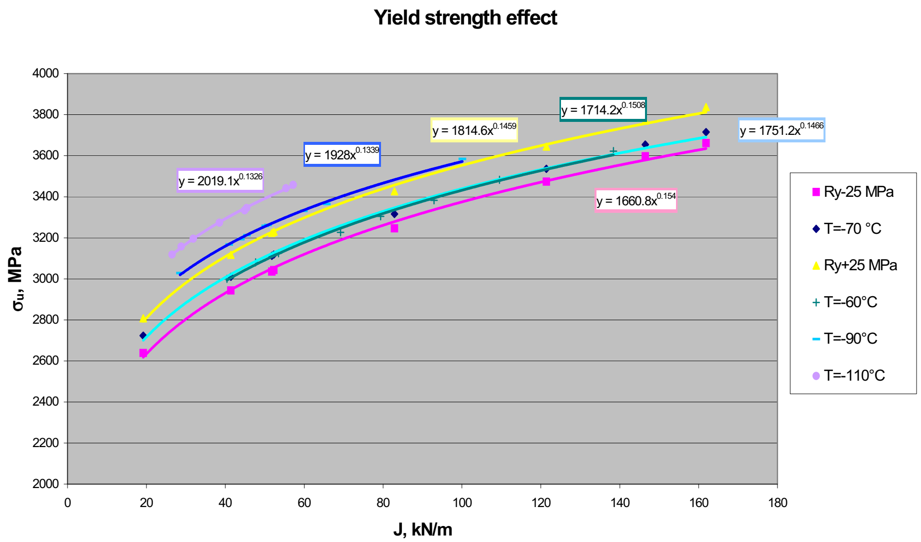

Fig. 4. Effect of the yield strength on the σ_u-J relationship determined by finite element analyses

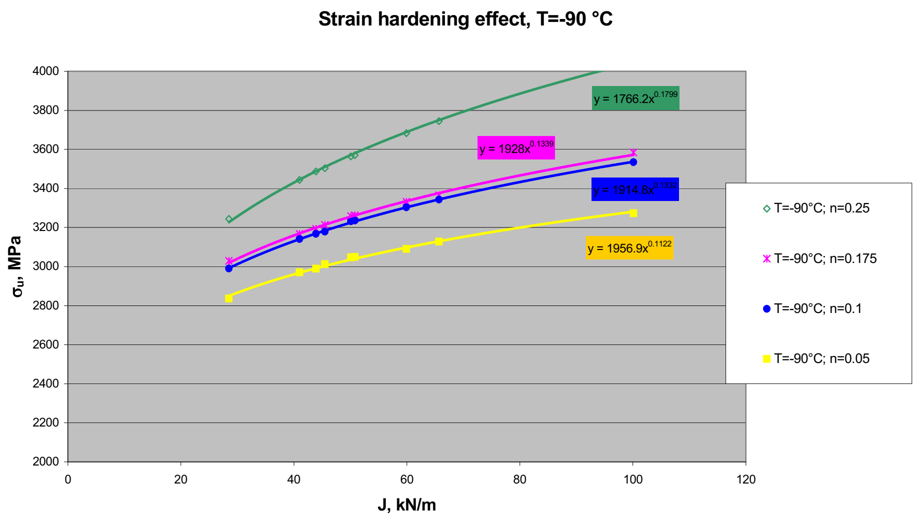

Fig. 5. Effect of hardening exponent on the σ_u-J relationship determined by finite element analyses

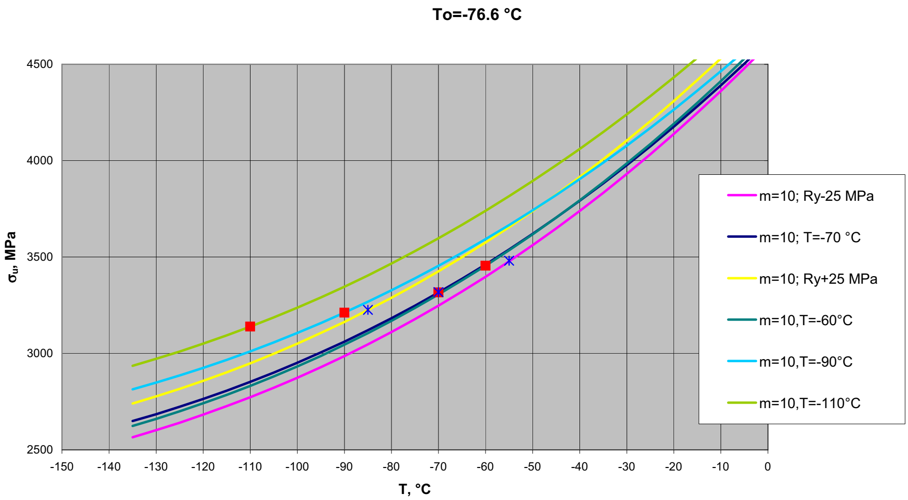

Fig. 6. Effect of the yield strength on the σ_u-T relationship

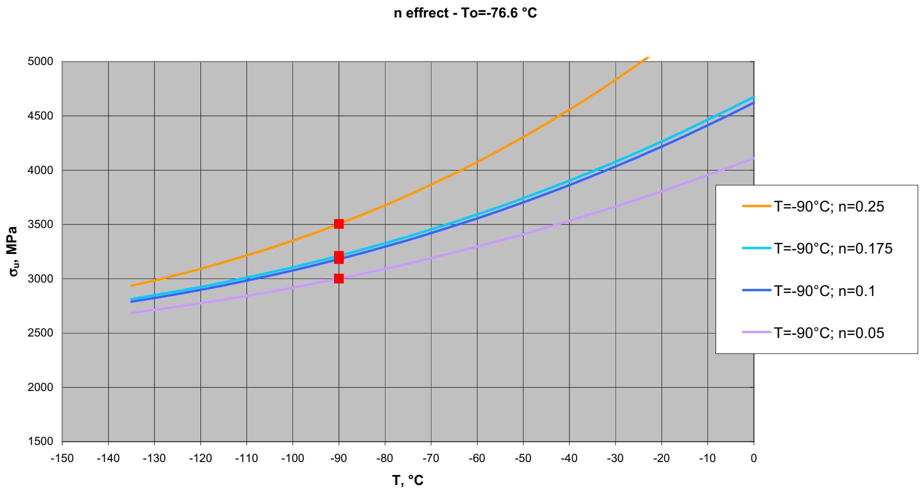

Fig. 6. Effect of strain hardening exponent on the σ_u-T relationship

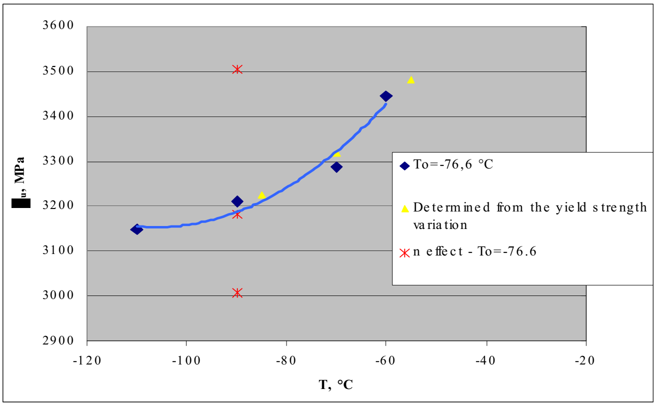

Fig. 7. Temperature dependence of σ_u (m=10) and effect of hardening exponent

Summary and conclusions

Based on the performed analyses on the effect of material parameters and temperature on the Beremin model parameter of JRQ reference RPV material, the following can be concluded:

- Both yield strength and strain hardening exponent have significant effect on the Beremin model parameter (σ_u) with fix m value. Therefore the scatter of these material properties should be taken in to account when applying Beremin model for prediction of brittle fracture probability.
- The predicted fracture probability (based on the two-parameter Beremin model) fits well with the experimental data if the measured material law is used, but for the lower temperature it is not enough to take into account only the changing of the yield strength, but also the change of the hardening exponent could be of importance.
- If the master curve describes well the material behaviour, it is possible to formulate the temperature dependence of σ_u - based on fracture toughness values measured at one temperature and the temperature dependence of the stress-strain curve of the material.

Acknowledgement

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