

FRACTURE TOUGHNESS TRANSITION OF FERRITIC-PEARLITIC STEEL AT STATIC AND DYNAMIC LOADING EVALUATED BY MASTER CURVE CONCEPT

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Resume

The paper focuses on assessing the usability of fatigue pre-cracked Charpy type specimens when evaluating the resistance of steel with ferritic-pearlitic structure to the initiation of unstable fractures. The suitability of using the specimens is evaluated on the basis of comparing experimentally established values of fracture toughness on pre-cracked Charpy type specimens and the values of this characteristics determined using Compact Tension (CT) specimens. For the evaluation and comparison of the fracture toughness temperature dependences determined on individual specimen types the master curve concept quantifying fracture toughness transition was applied. In the case of the steel employed, very good agreement was found to exist between the characteristics determined on individual types of specimen. It was shown that fracture toughness determined on pre-cracked Charpy type specimens can be regarded as a representative measure of resistance of the material employed to the brittle fracture occurrence.

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1. Introduction

In technical practice, the most vulnerable to exhibit unstable failures are components and structures in which the initiation or existence of crack failures can be expected. The probability of the occurrence of brittle fracture failure in a structure depends not only on internal factors such as the microstructure of material, but also on external effects, including temperature and loading rate in particular. For steels with ferritic base microstructure, the risk of brittle fracture occurrence increases sharply in steel structures operating (permanently or temporarily) in the transition region of the steel used or in structures exposed to dynamic mode of loading. Evaluation of the material resistance to the initiation of unstable fractures is in such cases based on parameters and characteristic

introduced by fracture mechanics. These include fracture toughness, defined as a resistance of material (structure) to the initiation of unstable fracture under the presence of a priori defects of the type of cracks.

Structures operating in a comparatively broad interval of temperatures and under conditions of static and dynamic loading include components of railway bogies, axles, wheels or wheelsets. Circumferential parts (rims) of railway wheels belong to the most stressed parts of these components where cracks can appear due to local overheating of the material during braking or as a result of fatigue loading at wheel/rail contact locations. Such defects once having critical dimensions can lead to brittle, unstable fractures being initiated along the whole profile of the wheel. According to the UIC 812-3 standard [1], the fracture

behaviour evaluation of railway wheel rims requires measuring the fracture toughness on specimens having 30 mm in thickness under conditions complying with the ASTM E 399 standard [2]. This is explained arguing that using specimens of greater thickness is less prone to the presence of microstructure gradients occurring, in particular, near the wheel rim surface. The microstructure heterogeneity is associated with the heat treatment technology used in the manufacture of the wheel, when during the spraying of the wheel rim a pronounced temperature gradient appears in the circumferential parts of the wheel. Thus there may exist microstructure regions (volumes) that satisfy the resistance criteria when 30 mm thick specimens are used but, simultaneously, with locally lower resistance to brittle failure. To record the local values of fracture toughness in the wheel rim it seems to be of greater advantage to use the PCVN type specimens (Pre-cracked Charpy V-Notch) loaded statically or dynamically by 3-point bending [3, 4]. One of the reasons for this modified approach is the possibility of localizing the specimen closer to the wheel tread. However, another reason is seen in refraining from the mechanical averaging of the actual material response and obtaining exact conditions for establishing the actual resistance to the brittle failure [5].

In the case of static and/or quasi static loading of steels with ferritic basic microstructure and the yield strength ranging from 275 to 825 MPa, the so-called fracture toughness master curve concept [6, 7] can be used to describe the temperature dependence of fracture toughness in the transition region. If the applicability of this approach was also proved for the case of dynamic loading,

it would be possible to predict not only the level of fracture toughness but also determine the failure probability in dependence on the two dominant external factors, temperature and loading rate [8].

2. Experimental material and testing methodology

The R7T ferritic-pearlitic steel was used as experimental material (Fig. 1), employed in the manufacture of railway wheelsets. Its chemical composition is given in Table 1.

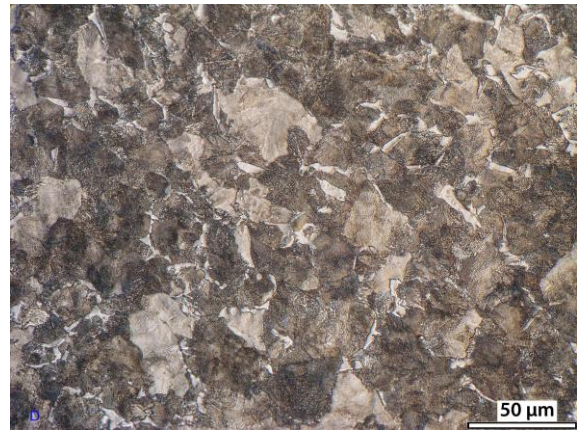


Fig. 1. Ferritic-pearlitic microstructure of R7T steel. (full colour version available online)

The fracture behaviour of pre-cracked specimens was examined exploiting Compact Tension (CT) specimens having 30 mm in thickness, corresponding to the UIC 812-13 standard [1] and referred to in the following as CT(30) specimens, In addition, pre-cracked Charpy V-notch (PCVN) specimens have been also employed. The locations of specimen extraction are shown schematically in Fig. 2. The PCVN specimens were taken from two locations, one closer to (location “I”) and one farther from (location “II”) the wheel tread.

Table 1

Chemical composition of steel R7T (in wt. %).

C	Mn	Si	Cr	Ni	Al	Cu	Mo	P	S	V	N
0.47	0.69	0.29	0.19	0.02	0.035	0.09	0.003	0.018	0.009	0.004	0.006

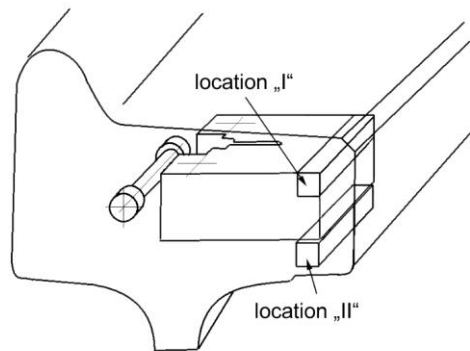


Fig. 2. Specimen localisation scheme in the wheel rim.

According to UIC 812-3, the fracture toughness is established based on the K_Q parameter for the instant of attaining force F_5 ; the F_5 is a force corresponding to the intersection point of the load F – displacement q trace and a straight line with the slope 5 % lower than the slope of the linear part of the $F - q$ record, even in case when the record continues after attaining this value (thus showing that elastic-plastic behaviour occurred). The fracture toughness established in this way represents a valid value K_{Ic} in some cases, in others only a provisional value K_Q . The measurement of static fracture toughness of CT(30) and PCVN specimens was conducted on a Zwick Z250 universal test machine at a loading rate of 1 mm/min while dynamic fracture toughness of PCVN specimens was measured on an instrumented impact tester at an impact rate of 1.5 m·s⁻¹ of the hammer tup. Unlike with PCVN specimens where fracture toughness was measured within a certain temperature interval, the static fracture toughness of CT(30) specimens was only determined at room temperature. The fracture toughness evaluation proceeded in keeping with standard procedures [9].

3. Results and discussion

3.1 CT(30) specimens, static loading

In the case of CT(30) specimens loaded statically at room temperature, two types

of the deformation and fracture mechanical response of material could be identified being quantified by the following parameters:

- a) linear elastic fracture toughness K_c (or K_Q according to UIC 812-3) with values lying in the interval from 60 to 90 MPa·m^{1/2}. In this case, no pronounced differences in the microstructure and hardness over the specimen thickness could be observed;
- b) elastic-plastic fracture toughness K_{Jc} (or K_Q according to UIC 812-3) after a larger elastic-plastic deformation in front of the crack tip and K_{Jc} values lying in the interval of 70 to 105 MPa·m^{1/2}. For specimens included in this group, greater differences in the microstructure and hardness over the specimen thickness could be observed than in the preceding case.

Irrespective of the nature of the failure, the mean value of fracture toughness K_Q determined on the CT(30) specimens was higher than the 80 MPa·m^{1/2} value prescribed in the UIC 812-3 standard (see Fig. 3).

3.2 PCVN specimens, static and dynamic loading

The temperature dependence of static and dynamic fracture toughness of PCVN specimens, together with the values established on CT(30) specimens can be found in Fig. 3. In the transition region, three types of fracture behaviour could be established in keeping with the general description of the fracture toughness temperature dependence which is given, for example, in [10]:

- i) K_c – fracture toughness fulfilling the conditions of linear-elastic fracture mechanics;
- ii) K_{Jc} – fracture toughness at the initiation of unstable fracture after preceding elastic-plastic deformation;
- iii) K_{Ju} – fracture toughness corresponding to the initiation of unstable fracture after a certain length of ductile tear.

The mean value of fracture toughness in dependence on temperature in the transition

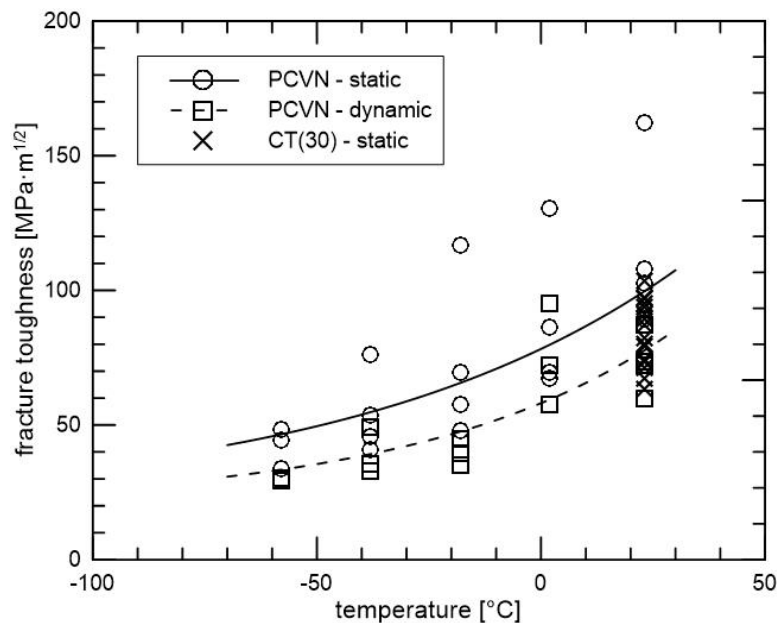


Fig. 3. Temperature dependence of static and dynamic fracture toughness of PCVN and CT(30) specimens.

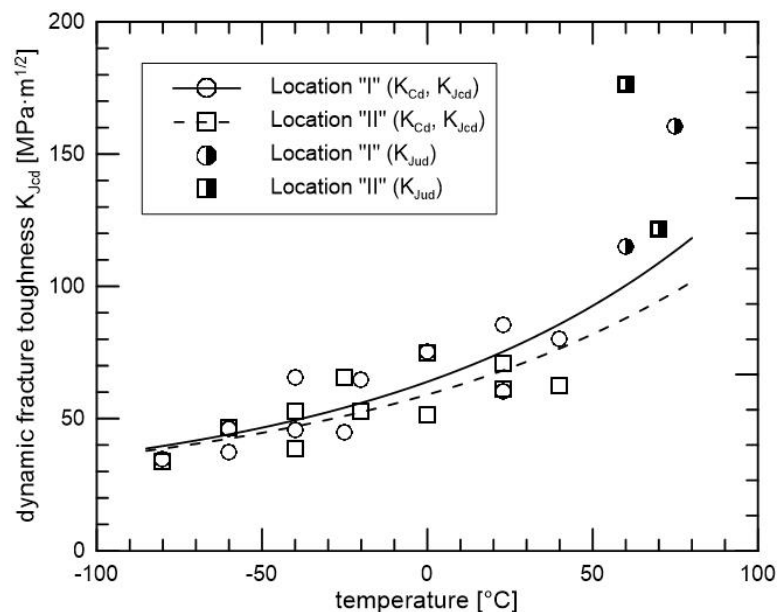


Fig. 4. Comparison of dynamic fracture toughness of PCVN specimens taken on sites "I" and "II".

region can be described by an exponential function in the form of $(K_C, K_{Jc})_{\text{mean}} = K_{\text{min}} + A \exp(BT)$. The value K_{min} given in the equation is the minimum fracture toughness value corresponding to the physical and technological principles, T is an absolute temperature. Choosing $K_{\text{min}} = 20 \text{ MPa}\cdot\text{m}^{1/2}$, the temperature dependence of the mean fracture toughness value obtained for quasi-static loading can be expressed in the form

$$(K_C, K_{Jc})_{\text{mean}} = 20 + 1.435 \exp(0.01356 T) \quad (1)$$

and for the case of dynamic loading in the form

$$(K_{Cd}, K_{Jcd})_{\text{mean}} = 20 + 0.280 \exp(0.01799 T) \quad (2)$$

Included in the calculation were in both cases only the values of fracture toughness satisfying the condition of limit value (validity

range) of fracture toughness K_{Jc} in the transition region given by relation [11]

$$(Eb_0R_{p0.2} / K_{Jc}^2) \geq 30 \quad (3)$$

where E is Young's modulus of elasticity, b_0 is the ligament, i.e. the length of the unbroken cross section in front of the fatigue crack ($W - a_0$), and $R_{p0.2}$ is the yield strength of material at a given temperature.

Fig. 4 gives a comparison of the temperature dependence of dynamic fracture toughness of PCVN specimens as obtained in locations "I" and "II". Experimental data was again fitted with exponential dependence in the form of $(K_c, K_{Jc})_{\text{mean}} = K_{\text{min}} + A \exp(BT)$. The graph reveals a modest decrease in the values of fracture toughness in the region of higher temperatures for specimens taken on the site farther from the wheel rim.

3.3 Fracture toughness correlation obtained using CT(30) and PCVN specimens

The quantification and prediction of the fracture toughness temperature dependence based on the fracture toughness master curve concept consists in the knowledge of the mean values shape of the fracture toughness temperature dependence established for specimens having thickness $B = 25$ mm (1T). This dependence can be described by the equation

$$K_{Jc(\text{med})} = 30 + 70 \exp[0.019 (T - T_0)] \quad (4)$$

where T_0 is the so-called reference temperature at which the fracture toughness median attains the value $K_{Jc(\text{med})} = 100 \text{ MPa}\cdot\text{m}^{1/2}$; units of T and T_0 are in °C. It has been proved [12, 13] that in steels with yield strength between 275 and 825 MPa the fracture toughness measured on 1T specimens and plotted in $(T - T_0)$ coordinates exhibits an identical temperature dependence as regards not only the transition curve shape but also the size of the scatter band. According

to the fracture toughness Master curve concept, the only parameter determining the transition behaviour is the position of reference temperature T_0 on the temperature axis.

It follows from the above that for the master curve concept to be applied, the fracture toughness values obtained via specimens of different sizes (thicknesses) must be adjusted to a thickness of 1T. To adjust the values of fracture toughness in the transition region, the following equation can be used [10, 14]

$$K_{Jc(B1)} = K_{\text{min}} + (K_{Jc(B)} - K_{\text{min}})(B/B_1)^{0.25} \quad (5)$$

where $K_{Jc(B1)}$ is the predicted value of fracture toughness for specimen having thickness B_1 , and $K_{Jc(B)}$ is the experimentally determined fracture toughness using a specimen of thickness B .

To estimate the size and shape of the scatter band of fracture toughness in the transition region, description via the Weibull three-parameter distribution can be used in the form

$$P_f = 1 - \exp\{-[(K_{Jc} - K_{\text{min}})/(K_0 - K_{\text{min}})]^m\} \quad (6)$$

where K_0 is the scale parameter and m the shape parameter (Weibull exponent). If $K_{\text{min}} = 20 \text{ MPa}\cdot\text{m}^{1/2}$ is chosen, then for the above-mentioned group of steels with ferritic basic microstructure the value m is approximately equal to 4. Equation (6) gives the probability of the failure (fracture initiation) for a random specimen from the set tested; the distribution function of the cumulative failure probability is independent of the specimen size and temperature.

The graph in Fig. 5 gives the temperature dependence of fracture toughness for CT(30) specimens. Since fracture toughness was only measured on CT specimens at room temperature, the temperature dependence after the correction of fracture toughness values

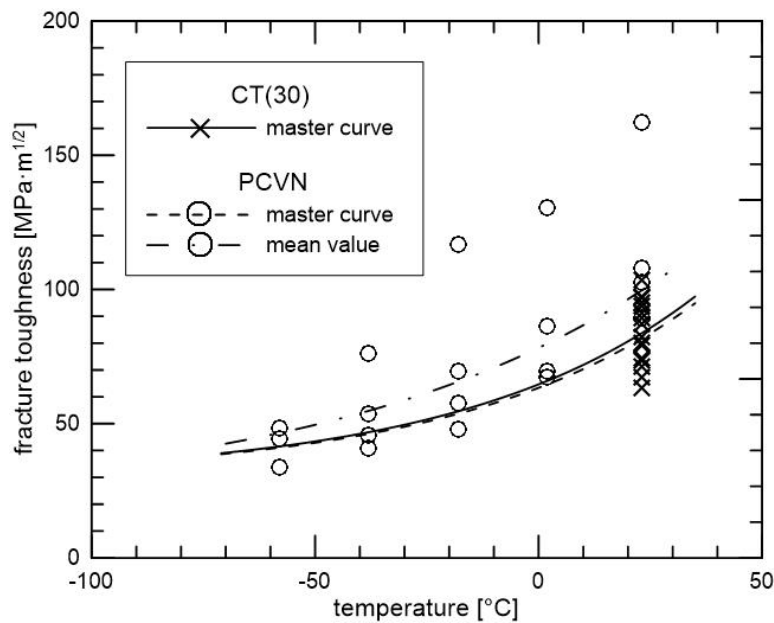


Fig. 5. Fracture toughness master curve for CT and PCVN specimens.

to the specimen thickness $1T$ (Eq. (5)) was calculated using the Master curve concept, see Eq. (4). The reference temperature of CT specimens of 25 mm in thickness ($1T$) was established as $T_{0(CT)} = 37\text{ °C}$ and the equation for temperature dependence can be given in the form

$$K_{Jc(\text{med}),CT(1T)} = 30 + 70 \exp[0.019 (T - 37)] \quad (7)$$

The same procedure was also applied to statically loaded PCVN specimens. After correction to the $1T$ thickness, the exponential function was fitted to the experimental data, and the reference temperature $T_{0(PCVN)} = 39\text{ °C}$ was established as the temperature corresponding to the median value of fracture toughness $K_{Jc(\text{med})} = 100\text{ MPa}\cdot\text{m}^{1/2}$. For PCVN specimens, the equation of the fracture toughness master curve can be written in the form

$$K_{Jc(\text{med}),PCVN(1T)} = 30 + 70 \exp[0.019 (T - 39)] \quad (8)$$

The above temperature dependence is also shown in graphic form in Fig. 5. In all the cases, only those fracture toughness values were included in the calculations that fulfilled the validity condition given by Eq. (3).

It is evident that the temperature dependence of fracture toughness expressed in the form of Master curves for CT and PCVN specimens is very similar. Also, the levels of the reference temperatures of the two types of specimen are almost identical, $T_{0(CT)} = 37\text{ °C}$ and $T_{0(PCVN)} = 39\text{ °C}$.

Experimental results obtained for the R7T steel, which is used in the railway wheelsets manufacture, indicate good agreement between quasi-static fracture toughness determined on CT(30) specimens and quasi-static and dynamic fracture toughness values established on pre-cracked Charpy type specimens. It can thus be concluded that PCVN specimens are suitable for the evaluation of resistance to unstable fractures, and that the characteristics obtained by means of these specimens represent both a local manifestation of fracture behaviour and the overall resistance of a given steel to brittle fracture initiation. Successful correlation, however, is conditioned by the fulfilment of certain conditions that result from the relation between the microstructure of the material and its fracture behaviour. They are, above all, the condition limiting the validity of fracture toughness values K_{Jc} (Eq. (3)), the condition of the applicability of the weakest link model and of the Weibull distribution

for the probability of fracture initiation, and finally the validity of the Master curve concept for the temperature dependence of the fracture toughness values in transition region.

4. Conclusion

a) The fracture toughness of R7T steel was determined under conditions of quasi-static and dynamic loading of pre-cracked Charpy V-notch type specimens taken from the surface of railway wheel rim. Due to impact loading, the mean values of dynamic fracture toughness at room temperature were by approximately $15 \text{ MPa}\cdot\text{m}^{1/2}$ lower compared to quasi-static fracture toughness.

b) The application of the fracture toughness Master curve concept was demonstrated for the fracture toughness determination related to specimens of standard thickness (1T) from data obtained on PCVN specimens, i.e. Charpy type specimens. Very good agreement was found between the reference temperatures T_0 for CT(30) (37 °C) and PCVN (39 °C) specimens.

c) The fracture toughness values determined on PCVN specimens can be regarded as a representative measure of the resistance of a given microstructure to unstable fracture initiation. As follows from a comparison with the fracture behaviour of CT(30) specimens this fracture toughness can be used not only for the evaluation of the local resistance of material to brittle failure but also for an overall evaluation of the resistance of material to this type of the fracture.

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