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The Ductile Crack Growth Effect on the Temperature Dependence of Cleavage Fracture Toughness

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ABSTRACT

The basic regularities of cleavage fracture after ductile crack growth are studied on the basis of a probabilistic model for cleavage fracture and deterministic model for ductile fracture proposed by the authors earlier. Investigations are performed as applied to a 2Cr-Ni-Mo-V reactor pressure vessel steel in the initial (as-produced) and embrittled states. For various temperatures, the dependencies of brittle fracture probability on stress intensity factor and the ductile tearing are calculated. For various states of a material, the temperature dependencies of cleavage fracture toughness are predicted with and without regard for ductile crack growth. The basic factors controlling the above dependencies are analyzed. The calculated results obtained are compared with test results of CT specimens.

KEY WORDS: cleavage fracture toughness, ductile crack growth, ductile tearing, J_R-curve, brittle fracture probability.

INTRODUCTION

At the present time the temperature dependence of fracture toughness at cleavage $K_{JC}^{cl}(T)$ and ductile $K_{JC}^{duct}(T)$ fracture is widely used for analysis of structure integrity of reactor pressure vessels (RPV). Such an analysis should on the one hand provide sufficient safety for RPV and, on the other hand, should decrease conservatism for estimation of the critical states. These opposite requirements may be reached if the known physical ideas about start and propagation of a crack on the cleavage and ductile mechanisms are considered.

These physical ideas can be summarized briefly as follows. Cleavage fracture in steels is of a statistical nature and, hence, is controlled by local properties of a material and can be described by the weakest link theory. As a result, a large scatter in K_{JC}^{cl} values is observed and a probabilistic approach should be used for description of $K_{JC}^{cl}(T)$ curve. In contrast, parameter K_{JC}^{duct} shows insignificant scatter as this parameter is determined for the ductile crack start on mechanism of nucleation, growth and coalescence of voids. Therefore $K_{JC}^{duct}(T)$ curve may be described in a deterministic statement.

Several interesting physical findings were revealed when testing a cracked specimen on fracture toughness. As known, when loading a cracked specimen at $K_I < K_{JC}^{duct}$ its brittle fracture occurs without the ductile crack growth. When $K_I = K_{JC}^{duct}$ a crack starts on the mechanism of ductile fracture. For subsequent loading at $K_I > K_{JC}^{duct}$, after some amount of ductile tearing, Δa, the brittle fracture of specimen may happen [1-4].

When taking into account the above particularities of brittle and ductile fracture the temperature dependence of fracture toughness may be schematically represented as shown in Fig. 1.

When evaluating the brittle strength of RPV the conservative estimation is usually used. It means that the curve a-b-c shown in Fig. 1 is used, at that the $K_{JC}^{cl}(T)$ curve at the brittle fracture probability $P_f \to 0$ (the curve a-b) is taken as the confidence curve, and the $K_{JC}^{duct}(T)$ dependence at $\Delta a=0$ (the curve b-c) is taken as the upper shelf. Conservatism for estimation of the critical states may be reduced over ductile fracture temperature range if some ductile crack extension $\Delta a>0$ is allowed that provides an increase of fracture toughness values on the upper shelf. However the problem arises how to predict the temperature dependence of fracture toughness at cleavage fracture over temperature range of ductile crack growth, $\left[K_{JC}^{cl}(T)\right]^{DCG}$.

As a common case, there exist three types of possible curves (curves 1, 2 and 3 in Fig. 1) which may be the cleavage fracture toughness curve over temperature range of ductile crack growth, i.e. $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curve.

- For curve 1: $\left[K_{JC}^{cl}(T)\right]^{DCG} = \left[K_{JC}^{cl}(T)\right]^{0}$, where $\left[K_{JC}^{cl}(T)\right]^{0}$ is the temperature dependence of cleavage fracture toughness calculated for $\Delta a=0$, i.e. curve 1 is taken when assuming that a character of the temperature dependence of cleavage fracture toughness $K_{JC}^{cl}(T)$ does not vary over temperature range of ductile crack growth.
- For curve 2: $\left[K_{JC}^{cl}(T)\right]^{DCG} > \left[K_{JC}^{cl}(T)\right]^{0}$.

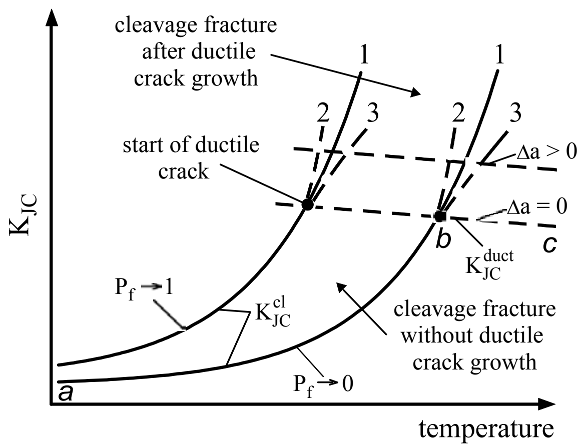

Fig. 1 The K_{JC}(T) curves (schematic)

- For curve 3: $\left[K_{JC}^{cl}(T)\right]^{DCG} < \left[K_{JC}^{cl}(T)\right]^{0}$.

To guarantee the conservative estimation for cleavage fracture toughness over temperature range of ductile crack growth it is necessary to know which of curves 1, 2 or 3 is the $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curve. If curve 1 or curve 2 was this curve, fracture toughness would be estimated conservatively over the whole temperature range when taking the same $K_{JC}^{cl}(T)$ curve both at $K_I \le K_{JC}^{duct}$ and at $K_I > K_{JC}^{duct}$. For example, the Master Curve may be taken as such $K_{JC}^{cl}(T)$ curve. If curve 3 is the $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curve, additional tests or calculations for constructing this curve should be performed.

In the present paper, prediction of the temperature dependence of cleavage fracture toughness over temperature range of ductile crack growth, $\left[K_{JC}^{cl}(T)\right]^{DCG}$ for RPV steel with various degree of embrittlement is presented. The prediction is performed by numerical modeling the cleavage fracture of cracked specimen after some amount of ductile crack growth. This modeling is based on the probabilistic model for cleavage fracture [5,6] and the deterministic model for ductile fracture [7,8].

THE PROBABILISTIC MODEL FOR CLEAVAGE FRACTURE

The probabilistic model for cleavage fracture based on local cleavage fracture criterion in a probabilistic manner is used [5,6]. According to this model the brittle fracture probability of a cracked specimen is written in the form [9]

$$P_f = 1 - \exp\left[-\left(\sigma_w / \tilde{\sigma}_d\right)^{\eta}\right], \tag{1}$$

where σ_w is the Weibull stress; $\tilde{\sigma}_d$ and η are temperature-independent Weibull parameters. According to [5,6] the Weibull stress σ_w is calculated as

$$\sigma_w = \left[\sum_{i=1}^{k}\left(\max\left(S_{nuc}^{i}\right) - \sigma_{d0}\right)^{\eta}\right]^{1/\eta} \tag{2}$$

Here $$S_{nuc}^{i} = \begin{cases} \sigma_{nuc}^{i}, \text{ if } \sigma_1^i \ge S_C(\kappa) \text{ and } \sigma_{nuc}^{i} > \sigma_{d0} \\ \sigma_{d0}, \text{ if } \sigma_1^i < S_C(\kappa) \text{ or } \sigma_{nuc}^{i} \le \sigma_{d0} \end{cases}, \qquad S_C(\kappa) = \left[C_1^* + C_2^* \exp(-A_d \kappa)\right]^{-1/2},$$

where $\max(S_{nuc}^{i})$ is the maximum value of S_{nuc}^{i} from the beginning of deformation up to the current moment of deformation of unit cell; i is the number of a unit cell; k is the number of unit cells in the cracked specimen; $\sigma_{nuc} \equiv \sigma_1 + m_T m_{\varepsilon}(\kappa)\sigma_{eff}$; σ_1 is the maximum principal stress; $m_T(T) = m_0\sigma_{Ys}(T)$; $m_\varepsilon(\kappa) = S_0/S_C(\kappa)$; $S_0 \equiv S_C(\kappa=0)$; $S_C(\kappa)$ is the critical brittle fracture stress; m_0 is a material constant; σ_{Ys} is the temperature-dependent component of the yield stress; the effective stress is $\sigma_{eff} = \sigma_{eq} - \sigma_Y$; σ_{eq} is the equivalent stress; σ_Y is the 0.2 offset yield stress; $\kappa = \int d\varepsilon_{eq}^{p}$ is Odqvist's parameter, $d\varepsilon_{eq}^{p}$ is the equivalent plastic strain increment; σ_{d0} is the Weibull parameter; C_1^*, C_2^*, A_d are material constants. The temperature–independent parameters $\tilde{o}_d$ and η in Eq. (1) are determined from test results of notched or cracked specimens at some (one) temperature [5, 6].

As a common case, for cracked specimen the parameter σ_w depends on stress intensity factor or J-integral. That is why, Eqs. (1) and (2) allow one to calculate dependence $P_f(K_I)$ or $P_f(J)$.

The stress and strain fields for a cracked specimen is calculated by FEM. The size of finite elements near the crack tip is taken to be of the order of 0.1 $\tilde{n}_{uc}^{cl}$, where $\tilde{n}_{uc}^{cl}$ is the size of the unit cell for modelling of cleavage fracture.

For the known stress and strain fields the brittle fracture probability of a cracked specimen is calculated by Eqs. (1) and (2). For this the whole cracked specimen is viewed as an aggregate of cubic unit cells with the size of $\tilde{n}_{uc}^{cl}$ and for each unit cell, the stress and strain fields are found by averaging over the unit cell volume.

THE DUCTILE FRACTURE MODEL

The earlier described ductile fracture model [7,8] is used. As a local criterion for ductile fracture the criterion of plastic collapse of a unit cell with size of $\tilde{n}_{uc}^{duct}$ is used:

$$dF_{eq} / d\text{æ} = 0 \, , \tag{3}$$

where $F_{eq}=\sigma_{eq}(1-S_\Sigma)$, S_Σ is the relative area of voids, i.e. area of voids per unit area of the unit cell section. In other words, F_{eq} is the stress in a conglomerate of matrix and voids, and σ_{eq} is the stress in the matrix of a material. The value of S_Σ is calculated by equations for void nucleation and growth according to the procedure presented in [7,8].

MODELING FOR CLEAVAGE FRACTURE AFTER DUCTILE CRACK GROWTH

Modeling for cleavage fracture after ductile crack growth is performed on the basis of the probabilistic model for cleavage fracture [5,6] and the deterministic model for ductile fracture [7,8] when using the calculation procedure consisting of two stages.

In the first stage, the ductile crack growth is simulated by FEM. The stress and strain fields for a specimen with ductile growing crack, the ductile tearing Δa and J-integral are calculated. In the second stage, the brittle fracture probability of a cracked specimen is calculated.

RESULTS

Prediction of the J_R-curves and Comparison with Test Results

The J_R-curves for 2T-CT specimens from 2Cr-Ni-Mo-V RPV steel in the initial and embrittled states predicted on the basis of the ductile fracture model are presented and compared with the test results. Embrittled state obtained by a special heat treatment that models radiation embrittlement of RPV steels. A degree of embrittlement was estimated from the temperature T_{41J} corresponding to the Charpy energy value of 41 J. According to [6] the value of T_{41J} for steel in the initial state was T_{41J} =-64°C and for steel in the embrittled state T_{41J} =116°C, so that ΔT_{41J} = 180°C.

In Fig. 2, the calculated J_R-curves, J(SZW+Δa), are represented for the initial and for the embrittled states; here SZW is stretch zone width. Fracture toughness test results from 2T-CT specimens obtained in [8] are also shown. As seen from Fig. 2 the calculation results agree with the experimental data, and temperature affects insignificantly on the J_R-curves.

Prediction of the Temperature Dependence of Fracture Toughness at Cleavage Fracture without Ductile Crack Growth

The temperature dependence of fracture toughness at cleavage fracture, $\left[K_{JC}^{cl}(T)\right]^0$, was predicted on the basis of the probabilistic model [5,6]. Calculations were performed by assuming that the ductile crack growth is absent for any load, i.e. at $K_{JC} > K_{JC}^{duct}$ it was taken that Δa=0. Calculations were performed for 2T-CT specimens. The unit cell size $\tilde{n}_{uc}^{cl}$ was taken to be equal to 0.05 mm [5,6]. Weibull parameters σ_{d0}, $\tilde{o}_d$ and η in Eqs. (1) and (2) are determined from test results of 2T-CT specimens: σ_{d0}=1593 MPa, $\tilde{o}_d$=17235 MPa and η=5.96 for steel in the initial state and σ_{d0}=1842 MPa, $\tilde{o}_d$=3600 MPa and η=12 for steel in the embrittled state.

The predicted $\left[K_{JC}^{cl}(T)\right]^0$ curves are shown in Fig. 3 for the initial and embrittled states at the brittle fracture probability P_f=0.05, 0.5 and 0.95. The experimental values of fracture toughness for 2T-CT specimens are also shown. As seen from Fig. 3, agreement between the calculated and test results is sufficiently good.

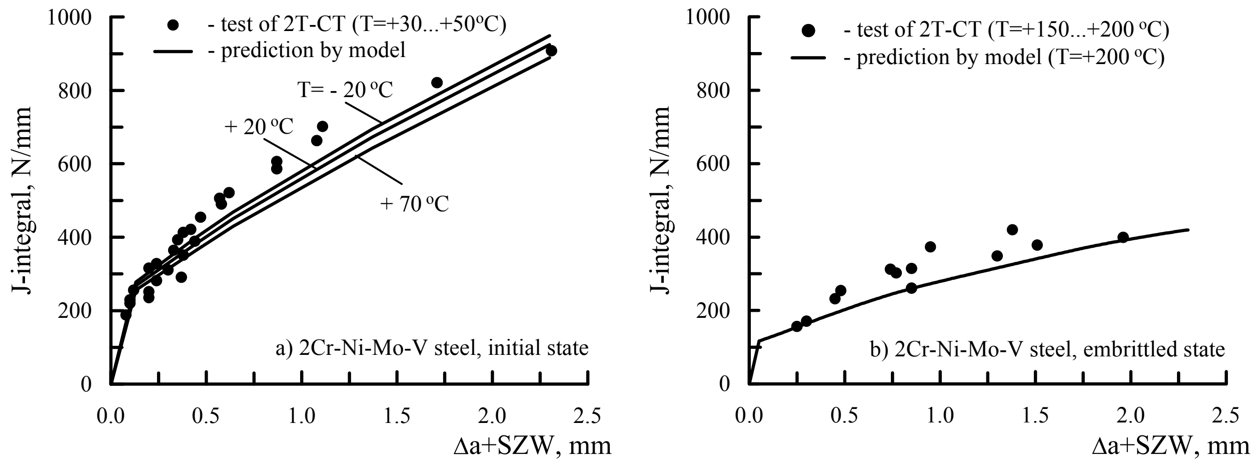

Fig.2 The predicted and the experimental J_R-curves for steel in the initial (a) and embrittled (b) states

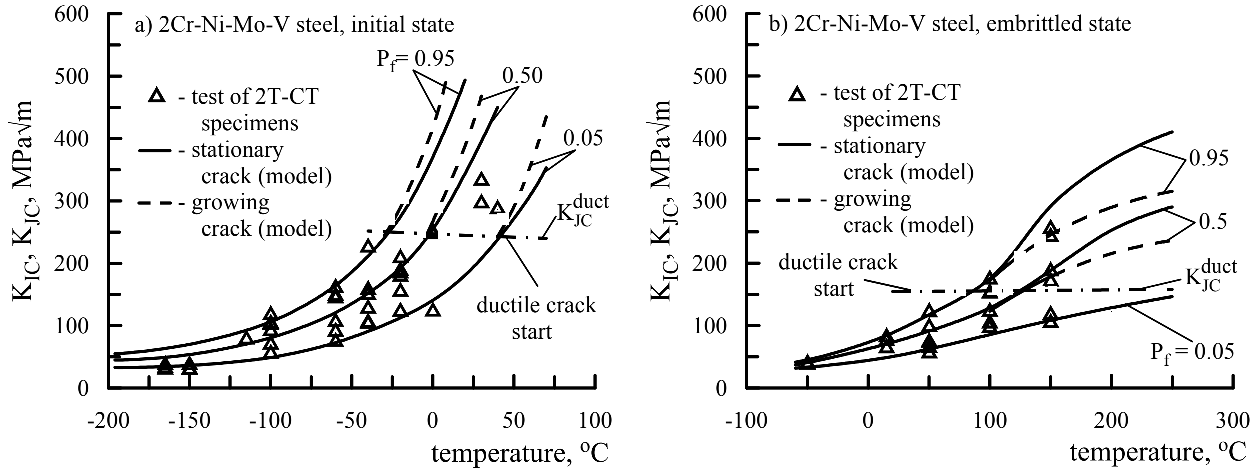

Fig.3 The $\left[K_{JC}^{cl}(T)\right]^{0}$ curves (the solid lines) and the $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curves (the dotted lines) for steel in the initial (a) and embrittled (b) states predicted with the probabilistic model: dots –experimental values for 2T-CT specimens

Prediction of the Temperature Dependence of Fracture Toughness at Cleavage Fracture after Ductile Crack Growth

In the first stage, FEM simulation of ductile crack growth provides the stress and strain fields for a specimen with ductile growing crack, the ductile tearing Δa and J-integral. In the second stage, the brittle fracture probability P_f of a cracked specimen is calculated as a function of Δa.

The dependencies $P_f(\Delta a)$ calculated are shown in Fig. 4 for the initial and embrittled states at various temperatures. As seen, the brittle fracture probability decreases as temperature increases that, from the physical point of view, is clear.

The dependence $J(\Delta a)$ may be constructed on the basis of the known function J(Δa+SZW) (Fig. 2), and the dependence $P_f(K_J)$ may be obtained from the known functions $P_f(\Delta a)$ (Fig. 4) and $J(\Delta a)$. Calculation of the dependence $P_f(K_J)$ was carried out also when predicting the dependence $\left[K_{JC}^{cl}(T)\right]^{0}$ (Fig. 3). In Fig. 5, the calculated dependencies $P_f(K_J)$ are shown for two cases: modeling for cleavage fracture with and without regard for ductile crack growth. It is seen that for material in the initial state, the brittle fracture probability for stationary crack is larger than for growing crack. Hence, for a given value of the brittle fracture probability, a value of K_{JC}^{cl} as calculated with regard for ductile crack growth will be higher than a value of K_{JC}^{cl} as calculated assuming that ductile crack growth is absent. The opposite picture is observed for the embrittled material.

The functions $P_f(K_J)$ calculated for various temperatures allow the prediction of the temperature dependence of fracture toughness at cleavage fracture after ductile crack growth, $\left[K_{JC}^{cl}(T)\right]^{DCG}$. This dependence calculated for a given probability of brittle fracture $P_f = 0.05$, 0.5 and 0.95 is presented in Fig. 3 by the dotted lines. It is seen from this figure, that at $K_{JC}^{cl} > K_{JC}^{duct}$, a character of the temperature dependence of fracture toughness varies. Comparison of Fig. 1 and

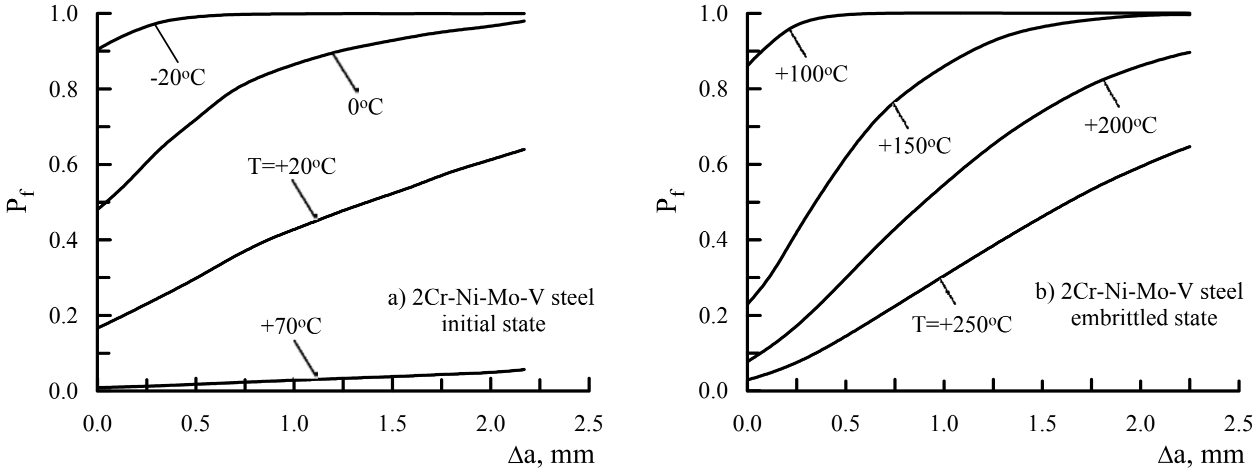

Fig.4 The calculated functions $P_f(\Delta a)$ for the initial (a) and embrittled (b) states at various temperatures

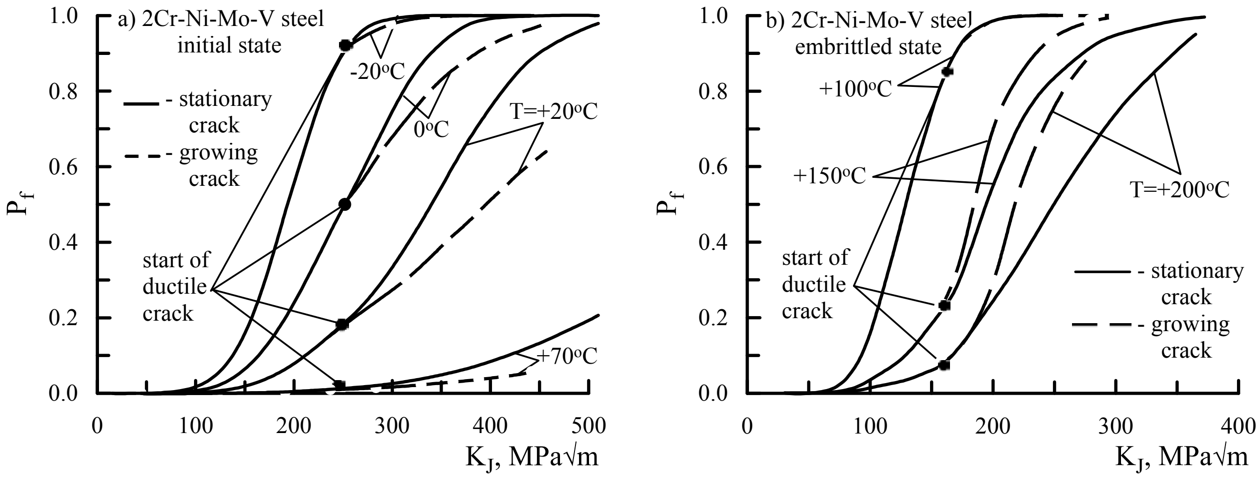

Fig.5 The brittle fracture probability P_f as a function of K_J for 2Cr-Ni-Mo-V steel in the initial (a) and embrittled (b) states when modeling cleavage fracture with regard for the ductile crack growth, Δa>0, (the dotted lines) and without regard for the ductile crack growth, Δa=0, (the solid lines)

Fig. 3 allows one to conclude that the dependence $\left[K_{JC}^{cl}(T)\right]^{DCG}$ for the initial state (Fig. 3a) is similar to curve 2 in Fig. 1, and for the embrittled state (Fig. 3b) is close to curve 3 in Fig. 1. This peculiarity will be in detail considered in the next section.

DISCUSSION

The results presented in Fig. 3 are very important for engineering application. Indeed, they show that over temperature range of ductile crack growth, firstly, a character of the temperature dependence of cleavage fracture toughness varies (compare $\left[K_{JC}^{cl}(T)\right]^{0}$ and $\left[K_{JC}^{cl}(T)\right]^{DCG}$) and secondly, for material in the initial state, the dependence $\left[K_{JC}^{cl}(T)\right]^{0}$ as predicted assuming that Δa=0 is conservative as compared with $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curve. For the embrittled material, the dependence $\left[K_{JC}^{cl}(T)\right]^{0}$ as predicted assuming that Δa=0 is not conservative as compared with $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curve.

For material in the initial state, the above finding is confirmed by available test data. In Fig. 6, experimental values of cleavage fracture toughness for CT specimens from 22NiMoCr37 steel are presented [10]. Test results of large number of specimens (more than 750 specimens) of various thickness from 12.5 to 100 mm are presented. The $K_{JC}^{cl}(T)$ curves are also given in Fig. 6 as calculated with the Master Curve approach [11] for the brittle fracture probability P_f=0.01 and 0.99. The fracture toughness curves in Fig. 6 correspond to the recalculated specimen thickness of 25 mm. As seen from Fig. 6, significant number of test results over fracture toughness value range $K_{JC}^{cl} > K_{JC}^{duct}$ are above the

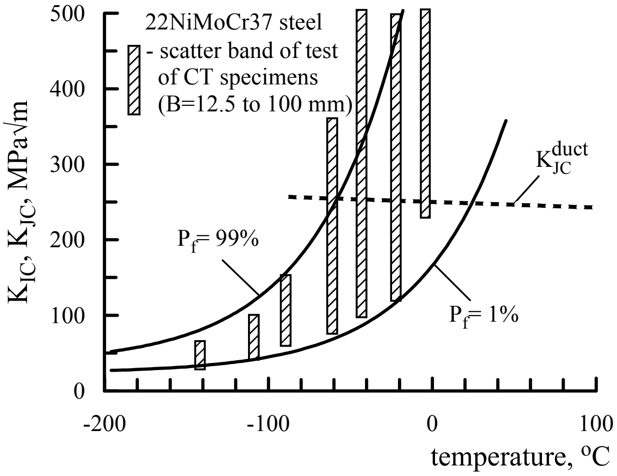

Fig. 6 Comparison between the scatter bands for experimental values of cleavage fracture toughness for CT specimens from 22NiMoCr37 steel [10] and the $K_{JC}^{cl}(T)$ curves as calculated with the Master Curve approach

Master Curve for P_f=0.99. This result shows that the $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curves are steeper than the $\left[K_{JC}^{cl}(T)\right]^{0}$ curves calculated assuming that Δa=0.

The ductile crack growth effect on fracture toughness was studied in many works, in particular, [12-14]. The $K_{JC}^{cl}(T)$ dependence in [13] was predicted by FEM simulation on the basis of the Rousselier ductile fracture model [15] and the Beremin cleavage fracture model [9]. By this it is shown that fracture toughness values with regard for ductile crack growth are larger than values calculated assuming that Δa=0.

This conclusion is in contradiction to results in [12,14]. According to [12,14], for material with any degree of embrittlement, the probability of cleavage fracture when ductile crack growth Δa exists may be calculated as

$$\left(\ln\frac{1}{1-P_f}\right)^{1/4} = \left(\frac{K_I - K_{min}}{K_0 - K_{min}}\right)\cdot\left(\frac{B}{B_0}\right)^{1/4}\cdot\left(1+\frac{2\Delta a\,\sigma_{flow}^2}{K_I^2\,\beta}\right)^{1/4}, \qquad (4)$$

where K_0 is a scale parameter; K_{min} is minimum value of fracture toughness; B is the specimen thickness; B_0 is the normalizing specimen thickness; $\sigma_{flow}=0.5(\sigma_Y+\sigma_u)$; σ_u is the ultimate strength; β is non-dimensional parameter.

It should be noted that as follows from (4), for a given probability of cleavage fracture we have $\left[K_{JC}^{cl}(T)\right]^{DCG} < \left[K_{JC}^{cl}(T)\right]^{0}$, i. e. the $\left[K_{JC}^{cl}(T)\right]^{DCG}$ curve will be similar to curve 3 in Fig. 1 for material both in the initial and embrittled states.

Above contradictions requires to analyse the assumptions taken for Eq. (4) deduction in detail.

When deducing Eq. (4) it was assumed that the brittle fracture probability is only controlled by a value of the plastic zone volume V_p and does not depend on peculiarities of stress and strain distribution over this zone. For stationary crack the plastic zone volume $V_p^{st} \sim K_I^4$, and for growing crack $V_p^{gr} \sim K_I^4 + f(\Delta a, K_I)$, where $f(\Delta a, K_I)$ is the plastic zone volume behind the crack tip. Then for the same value of stress intensity factor K_I, the brittle fracture probability for growing crack will be larger than for stationary crack and, hence, $\left[K_{JC}^{cl}(T)\right]^{DCG} < \left[K_{JC}^{cl}(T)\right]^{0}$.

Thus, calculation with formula (4) are in agreement with calculation performed for material in the embrittled state (see Fig. 3b) and in contradiction to our calculation for material in the initial state (see Fig. 3a).

From our point of view, formula (4) is not general for prediction of the $\left[K_{JC}^{cl}(T)\right]^{DCG}$ dependence as peculiarities of stress and strain distribution near the stationary and growing crack tip were not taken into account when deducing this formula. Besides, different contribution of stress and strain into the brittle fracture probability was not taken into account.

As seen from Eqs. (1) and (2), the brittle fracture probability is controlled by the parameter $\sigma_{nuc} \equiv \sigma_1 + m_T m_\varepsilon \cdot A_0 æ^n$. Difference between $\left[K_{JC}^{cl}(T)\right]^{DCG}$ and $\left[K_{JC}^{cl}(T)\right]^{0}$ for material in the initial and embrittled states, is determined by the different contribution of the first, σ_1, and second, $m_T m_\varepsilon \cdot A_0 æ^n$, components of the value σ_{nuc} into the brittle fracture probability. For material in the initial state, the ductile crack growth occurs at lower temperature than for the embrittled state. As the parameter m_T increases as temperature decreases then for material in the initial state, the second component of σ_{nuc} which depends on plastic strain, exerts the dominant influence on the brittle fracture probability. As degree of embrittlement of a material increases, the ductile crack growth occurs at higher temperature and, hence, the contribution of the second component of σ_{nuc} into the brittle fracture probability decreases, and the contribution of the first component increases.

Besides, value of the plastic strain near the crack tip is different for stationary and ductile growing cracks. As K_I increases at $K_I > K_{JC}^{duct}$, the plastic strain near the ductile growing crack tip does not exceed value of critical strain for ductile fracture, while plastic strain near the stationary crack tip increases without restriction. As a result, at the same value $K_I > K_{JC}^{duct}$, plastic strain is lower near the ductile growing crack tip than near the stationary one. At the same time, the maximum principal stresses σ_1 near the ductile growing crack tip exceed the stresses near the stationary crack tip insignificantly [8].

According to formulae (1) and (2), a working volume controlling the brittle fracture probability near the growing crack consists of both the plastic zone ahead the growing crack tip and the plastic zone behind the crack tip. It is clear that at the same K_I the working volume for stationary crack is practically equal to the plastic zone ahead the crack tip and it is less than for growing crack.

Thus, at the same value of K_I, the differences between stationary and growing crack consist of the following: the working volume near stationary crack is less than near growing crack; the strain level near stationary crack is higher than near growing crack; the level of the σ_1 stress near the stationary crack tip is practically equal to the level of the σ_1 stress near growing crack.

As follows from the represented analysis, for case if strain provides the dominant contribution in probability, the situation is possible when the brittle fracture probability for stationary crack will be larger than for growing crack and, hence, $\left[K_{JC}^{cl}(T)\right]^0 < \left[K_{JC}^{cl}(T)\right]^{DCG}$. Such a case is typical for material in the initial state and, it seems for slightly embrittled material. By this, as a resistance to brittle fracture of a material increases and, hence, temperature of the beginning of ductile crack growth decreases and m_T increases, the difference between $\left[K_{JC}^{cl}(T)\right]^0$ and $\left[K_{JC}^{cl}(T)\right]^{DCG}$ increases.

Thus, for initial and slightly embrittled state, fracture toughness estimation will be conservative over the whole temperature range, if the dependence constructed on the basis of fracture toughness test results over range $K_{JC}^{cl} \le K_{JC}^{duct}$, is used and extrapolated over range $K_{JC}^{cl} > K_{JC}^{duct}$.

For case if the σ_1 stress provides the dominant contribution in the brittle fracture probability, the brittle fracture probability for stationary crack will be less than for growing crack and, hence, $\left[K_{JC}^{cl}(T)\right]^0 > \left[K_{JC}^{cl}(T)\right]^{DCG}$. This case is typical for highly embrittled material. By this, as a degree of embrittlement of a material increases, the difference between $\left[K_{JC}^{cl}(T)\right]^{DCG}$ and $\left[K_{JC}^{cl}(T)\right]^0$ increases.

CONCLUSIONS

1. Predictions of the temperature dependence of cleavage fracture toughness $K_{JC}^{cl}(T)$ have been performed on the basis of a probabilistic model for cleavage fracture and deterministic model for ductile fracture as applied to a 2Cr-Ni-Mo-V reactor pressure vessel steel in the initial (as-produced) and embrittled states. Predictions have been performed for cases when the K_{JC}^{cl} value is less than the upper shelf level K_{JC}^{duct} and when $K_{JC}^{cl} \ge K_{JC}^{duct}$. It has been shown that a character of the dependence $K_{JC}^{cl}(T)$ varies for $K_{JC}^{cl} > K_{JC}^{duct}$, i.e. when the ductile tearing exists, $\Delta a>0$.

2. For material in the initial state, cleavage fracture toughness calculated with regard for ductile crack growth, $\left[K_{JC}^{cl}(T)\right]^{DCG}$, exceeds cleavage fracture toughness calculated without regard for ductile crack growth, $\left[K_{JC}^{cl}(T)\right]^0$. Therefore the dependence $\left[K_{JC}^{cl}(T)\right]^0$ may be used as a conservative estimation for the K_{JC}^{cl} curve over range $K_{JC}^{cl} \ge K_{JC}^{duct}$. In particular, the dependence obtained on the basis of fracture toughness test results over range $K_{JC}^{cl} < K_{JC}^{duct}$ may be extrapolated over range $K_{JC}^{cl} \ge K_{JC}^{duct}$.

3. For material in highly embrittled state, fracture toughness $\left[K_{JC}^{cl}(T)\right]^{DCG}$ is less than fracture toughness $\left[K_{JC}^{cl}(T)\right]^0$.

4. The difference between the dependencies $\left[K_{JC}^{cl}(T)\right]^{DCG}$ and $\left[K_{JC}^{cl}(T)\right]^0$ depends on degree of material embrittlement. The effect of material embrittlement degree on cleavage fracture toughness after ductile crack growth is explained by the different relative contribution of the plastic strain and the maximum principal stress into the brittle fracture probability. The more significant the contribution of plastic strain, the more probable that $\left[K_{JC}^{cl}(T)\right]^{DCG}$ will

exceed $\left[K_{JC}^{cl}(T)\right]^0$. For material in the initial state, the contribution of plastic strain into the brittle fracture probability prevails as compared with the contribution of the maximum principal stress σ_1, and $\left[K_{JC}^{cl}(T)\right]^{DCG} > \left[K_{JC}^{cl}(T)\right]^0$. As a degree of embrittlement of a material increases, the relative contribution of the plastic strain decreases and, for material with high degree of embrittlement, $\left[K_{JC}^{cl}(T)\right]^{DCG} < \left[K_{JC}^{cl}(T)\right]^0$.

NOMENCLATURE

K_I	- stress intensity factor
K_{JC}^{cl}, $K_{JC}^{cl}(T)$	- fracture toughness at cleavage fracture, the temperature dependence of fracture toughness at cleavage fracture
SZW	- stretch zone width
Δa	- ductile tearing (without regard for SZW)
K_{JC}^{duct}, $K_{JC}^{duct}(T)$	- fracture toughness at ductile fracture and Δa=0, the temperature dependence of fracture toughness at ductile fracture
$\left[K_{JC}^{cl}(T)\right]^0$	- the predicted temperature dependence of fracture toughness at cleavage fracture without regard for ductile crack growth (Δa=0)
$\left[K_{JC}^{cl}(T)\right]^{DCG}$	- the predicted temperature dependence of fracture toughness at cleavage fracture with regard for ductile crack growth (Δa>0)
P_f	- the brittle fracture probability

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