LOCAL CRITERION FOR CLEAVAGE FRACTURE AND FRACTURE TOUGHNESS PREDICTION

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Cleavage fracture of pearlitic steels under various loading history is investigated. It has been experimentally shown that for steels after static prestrain by tension and cyclic prestrain brittle fracture critical stress is described by increasing function of Odqvist's parameter, in the same time plastic precompression results in the significant embrittlement of steel and transition from transcrystalline cleavage fracture to intercrystalline one. New local criterion for cleavage fracture is formulated. This criterion application to predict fracture toughness dependence on temperature $K_{IC}(T)$ and prestrain influence on K_{IC} is shown.

INTRODUCTION

At present as a wide-spread formulation of cleavage fracture criterion one usually uses the equations

$$\sigma_{eq} \geq \sigma_Y \quad \text{(1a)}$$

$$\sigma_1 \geq S_C \quad \text{(1b)}$$

Condition (1a) is a necessary condition for brittle fracture and describes cleavage microcrack nucleation. Condition (1b) being a sufficient one determines microcrack propagation condition.

Criterion (1) application gives adequate prediction for critical states of specimens with notchs and cracks in a series of cases. In particular, criterion (1) was successfully used by Knott (1) and Ritchie et al (2) for prediction of the temperature dependence of $K_{IC}(T)$ for low

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strength steels. Nevetheless by using criterion (1) for middle and high strength steels having the low ratio S_C/σ_Y the prediction of $K_{IC}(T)$ is not adequate to experimental data in low temperature range. For indicated steels there is a temperature range for which condition (1b) is reached early then condition (1a). That's why condition (1a) is fulfiled at the higher value of K_{IC} with temperature decreasing. It is usually assumed that in this temperature range K_{IC}=const.

In this paper the necessary and sufficient conditions of brittle fracture criterion are modified on the base of physical-and-mechanical modelling for cleavage microcrack behaviour. New formulation allows to predict adequately dependence $K_{IC}(T)$ and prestrain influence on K_{IC}.

CRITICAL BRITTLE FRACTURE STRESS ANALYSIS

Investigation performed by Margolin and Shvetsova (3) allowed to draw the following conclusion. S_C is low-sensitive to temperature parameter, which defines condition for cleavage microcrack start and propagation through barriers formed at plastic deformation. This condition may be written as

$$\sigma_1 \geq S_C(\chi) \qquad \text{.........}(2)$$

$S_C(\chi)$ in (2) is monotonous increasing function of accumulated plastic strain only. S_C increase in deformed material is connected with formation of material deformation substructure, boundaries of which are additional barriers for cleavage microcracks. The based on this idea model for S_C prediction was elaborated in (3). According to this model $S_C(\chi)$ is defined as

$$S_C=(c_1+c_2\exp(-A\chi))^{-1/2} \qquad \text{.........}(3)$$

The influence of static prestrain by tension and cyclic prestrain on S_C was experimentally investigated as applied to middle strength Cr-Mo-V steels (3). Results of tests performed confirmed the functional type of dependence (3) (Fig.1). At the same time there are experimental data obtained by Beremin (4) which show that S_C may decrease after plastic precompression. This phenomenon has been explained not satisfactory.

To investigate this phenomenon tests for determination of S_C in Cr-Mo-V steel after plastic precompression were performed. Precompression was carried out at temperature T=20°C up to values of plastic strain ε^p_{com}=10,20,30 and 40%. Smooth cylindrical specimens machined from precompressed steel were ruptured by tension at T=-196°C. Results of these tests are shown in Fig.1. It is seen precompression leads to significant decrease of critical fracture stress S_C. For comparision in Fig.1 the relation of $S_C(\chi)$ for steel in initial state and state after plastic prestrain is represented.

Fractographic investigation of fracture surfaces of specimens after various plastic prestrain, ruptured by tension at T=-196°C, shows the followings. Brittle fracture mechanism for specimens in initial state and state after static and cyclic prestrain is transrystalline cleavage and microcleavage. This mechanism is known to be typical for both pearlitic steels and another BCC-metals. Fracture surfaces of specimens after precompression are characterized by intercrystalline fracture regions. The fraction of such regions in fracture surface increases with ε^p_{com} increase.

Thus, experiments performed show that plastic precompression results in the significant embrittlement of steel and transition from transcrystalline cleavage fracture to intercrystalline one. Such change of brittle fracture mechanisms caused by plastic prestrain is phenomenon unknown formerly as it may be considered from existed publications. The following physical mechanism of material embrittlement and scheme of transition from transcrystalline to intercrystalline fracture may be proposed. It may be shown that intercrystalline brittle fracture for precompressed steel is caused by intercrystalline void nucleation and their transformation under precompression into sharp microcracks. At the following tension such microcracks appear to be an initiators for intercrystalline brittle fracture. Scheme for fracture of material precompressed up to some strain ε^p_{com} and ruptured by tension at different temperatures is shown in Fig.2. At $T<T_0$ intercrystalline fracture is realized at $\sigma_1=S^I_C$ and $\sigma_{eq}<\sigma_Y^{com}$, by this sharp intercrystalline microcracks are not blunted and their propagation leads to intercrystalline fracture of specimen. At $T>T_0$ fracture is transcrystalline and happens at $\sigma_1=S_C(\chi)$ and $\sigma_{eq}>\sigma_Y^{com}$ by this intercrystalline microcracks are blunted and transform into voids and transcrystalline cleavage fracture happens from new sharp microcracks nucleated under tension. Temperature of fracture mechanism transition T_0 and critical stress of intercrystalline fracture S^I_C depend on ε^p_{com}. Decreasing dependence $S^I_C(\varepsilon^p_{com})$ is explained by increase of size of intercrystalline voids nucleated under precompression.

ANALYSIS OF CLEAVAGE MICROCRACK NUCLEATION CONDITION

As a criterion of microcrack nucleation, condition (1a) is usually used. However, not any microcracks but only sharp ones, i.e. microcracks which are able to unstable growth at the moment of their nucleation are important for brittle fracture. As shown in (3) nucleation condition of sharp microcracks does not coincide with (1a) and in common case may be formulated as

$$\sigma_1+m(\sigma_{eq}-\sigma_o)=\sigma_d \qquad (4)$$

where $m=m_o(T)(c_1+c_2\exp(-A\chi))^{1/2}$. For m and σ_d it is possible to give the following physical interpretation. Depending on concrete mechanism of microcrack nucleation, stress σ_d may be the strength of matrix or inclusion or "matrix-inclusion" boundary. Parameter m characterizes geometry of dislocation pile-up: m is concentration coefficient for local stress in the pile-up tip. To determine parameters m and σ_d experimental-calculated procedure based on the fracture data for cylindrical notched specimens was developed in (3). For such specimens the condition of microcrack propagation (2) takes place earlier than the condition of their nucleation (4). In this case the brittle fracture of specimens is controlled by the condition (4) only. Parameters m and σ_d were determined for pearlitic Cr-Mo-V steel.

The suggested criterion of brittle fracture includes the conditions of microcrack nucleation (4) and propagation (2).

FRACTURE TOUGHNESS PREDICTION

Suggested criterion of the brittle fracture was used to predict $K_{IC}(T)$. For analytical description of curve $K_{IC}(T)$ the following positions are taken (3).

1. At $K_I=K_{IC}$ (T) the local fracture criterion must be fulfilled in the region near the crack tip. From the physical point of view the given requirement means the realization of contrary fracture mechanism by which the microdamages nucleated near the crack tip are united with it.

2. Fracture analysis is carried out in the polycrystal grain which is the nearest to the crack tip since the fracture condition is fulfilled in it earlier then in grains located at a more distance from the crack tip.

3. Stress-strain analysis in the nearest grain is carried out for the case of plane strain in finite strain statement (a change of a crack-tip blunting is taken into account) on the base of the approximated analytical solution (3).

A calculated curve $K_{IC}(T)$ obtained for Cr-Mo-V steel is presented in Fig.3. At temperature from -196° to 20°C the brittle fracture is realized according to condition (4), i.e. microcrack nucleation but not propagation is a critical event. At T>20°C parameter K_{IC} is determinated by ductile fracture criterion.

For Cr-Mo-V steel after pretension 6% (T=20°C) fracture toughness K^*_{IC} was calculated. At T=-60°C value K^*_{IC} for deformed steel is approximately equal to value K_{IC} for initial state, but at -196° $K^*_{IC}=0.5K_{IC}$. Such calculated result which agrees with experimental data, is highly important since by the use of well-known models (for example, RKR-model (2)) in which traditional formulation of brittle fracture criterion is applied it is impossible to explain the decrease of the lowest shelf $K_{IC}(T)$.

SYMBOLS USED

A = material constant

c_1, c_2 = material constants (MPa^{-2})

K_{IC} = fracture toughness ($MPa\sqrt{m}$)

S_C = critical brittle fracture stress (MPa)

ε^p_{eq} = equivalent plastic strain

χ = Odqvist's parameter

σ_1 = the maximum principal stress (MPa)

σ_o = friction stress (MPa)

σ_{eq} = equavalent stress (MPa)

σ_Y = yield stress (MPa)

σ_Y^{com} = yield stress for precompressed specimen (MPa)

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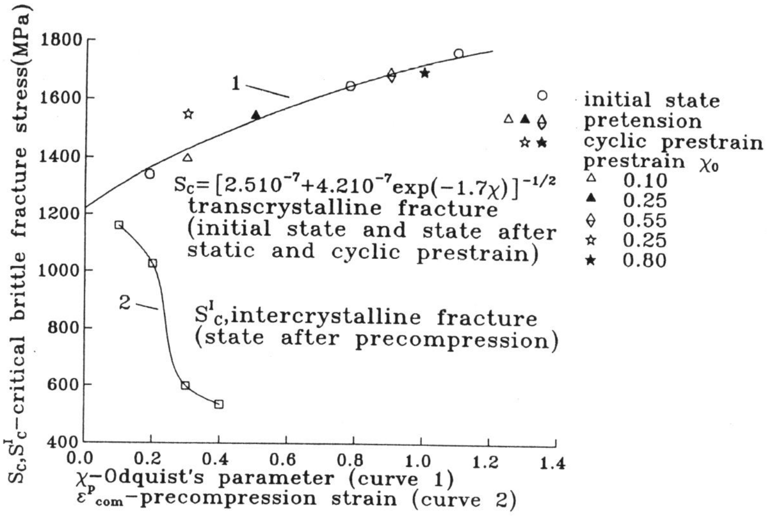
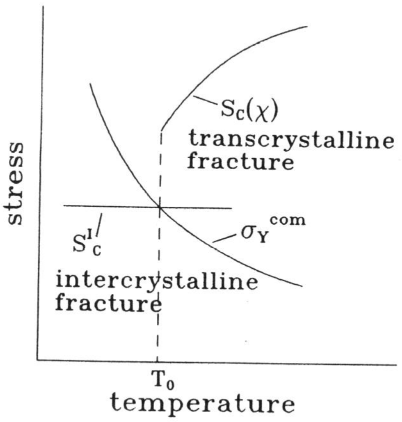


Figure 1. Critical brittle fracture stress vs plastic strain.



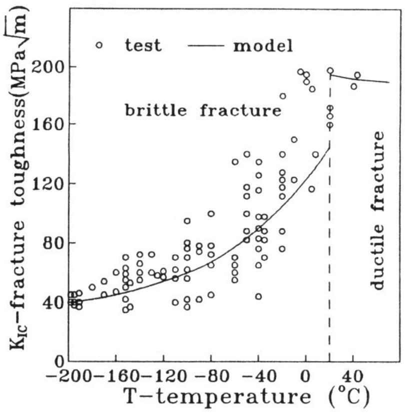


Figure 2. Brittle fracture for precompessed steel (scheme).

Figure 3. Fracture toughness vs temperature for Cr-Mo-V-steel.