AN ANALYSIS OF THE BRITTLE FRACTURE MECHANISM IN CAST STEEL

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A model of brittle fracture (RKR) has been verified experimentally for cast steel. Smooth samples were tested in tension to determine the yield stress in temperature range from +20°C to -196°C while the stress of brittle fracture has been measured in four point bending tests. The toughness of the tested cast steel has been estimated by critical J integral evaluation. In addition, the fractured surfaces have been examined together with precipitates identification using replica technique and thin foils examination. To calculate the process zone size, the stress distribution in accordance with HRR solution has been used. The experimentally determined critical fracture stress value has been compared with the one calculated using Griffith equation and a good agreement has been obtained. The results of testing have elucidated the process of crack initiation in the examined material.

INTRODUCTION

To describe the brittle fracture of cast steel, a model developed by Ritchie, Knott and Rice (RKR) has been accepted. In accordance with this model the brittle fracture occurs when the stress in process zone is equal to the critical stress of brittle fracture. The process zone size situated in the vicinity of crack tip has not been consistently determined yet. In early papers (1) it was assumed that the process zone is equal to two grain diameters. Further experiments exhibited that the size of this zone depends rather on the distribution of precipitates in metal alloys (2). However, the dependence of process zone size on temperature was not investigated so far. In the present paper this problem has been studied.

Material

The material was low carbon cast steel after normalizing and annealing. The chemical composition was as follows: C-0.18%, Mn-1.06%, Si-0.52%, S-0.018%, P-0.016%.The mechanical properties (yield stress, ultimate tensile stress, elongation and reduction of area) have been determined in temperature range from +20°C to -196°C. The obtained data are presented in Table 1.

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TABLE 1 - Mechanical properties of the tested cast steel.

Temperature °C	Yield stress MPa	UTS MPa	Elongation A_5 %	Reduction of area z %
20	282.1	504.2	36.0	64.6
-30	335.8	552.8	36.2	64.1
-45	362.3	571.2	35.7	62.1
-60	346.3	588.9	37.7	63.2
-120	451.2	660.3	33.2	55.8
-196	749.3	827.3	9.7	12.5

In addition the stress-strain courve has been described with the help of the Ramberg-Osgood equation in the form of :

$$\frac{\varepsilon}{\varepsilon_o} = \alpha_o \left(\frac{\sigma}{\sigma_o}\right)^n \tag{1}$$

where : ε_o - yield strain

σ_o - yield stress

α_o - material constant = 5.75

n - hardening coefficient = 4.75

The fracture toughness has been mesured in agreement with ASTM Standard using 3-point bending samples. The thickness of samples was equal to 15 mm. The critical values of J-integrals J_{Ic} and the critical values of stress intensity factor K_{Ic} calculated from J_{Ic}at a temperatures between +20 °C and -196°C are given in Table 2.

TABLE 2 - Fracture toughness of the tested cast steel.

Temperature °C	J_{Ic} kN/m	K_{Ic} MPa*m$^{1/2}$
20	212.7	221.6
-30	295.1	261
-45	267.3	248.4
-60	125.6	170.2
-120	39.3	95.3
-196	8.56	44.4

To calculate the process zone sizes, the critical stress of brittle fracture has to be known. This stress was determined experimentally on the notched four point bending samples using Griffith-Owen method (3). The tests have been made at a temperature of -196°C. The critical stress values are given in Table 3. In samples Nos. 2, 4, 7 failure was preceded by twinning and in these cases the critical stresses values were higher. Therefore, for further analysis the mean value of critical brittle fracture stresses for samples where twinning was not observed was taken. This mean value is $\sigma_C = 1475$ MPa . As it was shown by Knott, the brittle fracture stress is temperature independent. This value was used for process zone size calculation at all temperatures.

TABLE 3 - Critical stress of the brittle fracture.

Number of sample	1	2	3	4	5	6	7	8
Critical stress MPa	1383.6	1554.7*	1435.7	1532.4*	1428.3	1339.0	1336.6*	1495.2

* failure preceded by twinning

Process zone size estimation

In this study it was assumed that RKR model is valid. To determine stress distribution in the vicinity of the crack tip, the HRR singularity has been used in the form of :

$$\sigma_{yy} = \sigma_y \left(\frac{J}{\alpha_o * \sigma_o * \varepsilon_o * I_n * r} \right)^{\frac{1}{n+1}} * \tilde{\sigma}_{yy}(\theta, n) \qquad (2)$$

where : σ_{yy} - normal stress perpendicular to crack plane equal to σ_C (Table 3)

J_{Ic} - critical value of J - integral (Table 2)

n - hardening coefficient = 4.75 (eq.1)

σ_o - yield stress (Table 1)

α_o - Ramberg-Osgood coefficient = 5.75 (eq.1)

ε_o - strain corresponding to yield stress ($\varepsilon_o = \sigma_o / E$)

r - distance from the crack tip

I_n , $\tilde{\sigma}_{yy}$ - coefficients depending on the hardening and stress state, taken from (4) ($I_n = 5.26, \tilde{\sigma}_{yy} = 2.26$)

Assuming that σ_{yy} equals the critical stress of brittle fracture σ_C ,the process zone size equal to "r" was calculated from eq.(2). The calculated process zone sizes are given in Table 4. In this table there are presented the process zone sizes calculated for temperatures from +20°C to -196°C. For comparison the data concerning the ductile fracture in the range of temperatures from +20°C to -45°C were taken from (5)

TABLE 4 - Process zone size (PZS)

Temperature °C	Yield stress MPa	J_{Ic} MJ/m^2	PZS µm	Note
20	282.1	0.210	503	ductile fracture
-30	335.8	0.295	503	ductile fracture
-45	362.3	0.267	605	ductile fracture
-60	346.3	0.125	225	brittle fracture
-120	451.2	0.039	203	brittle fracture
-196	749.3	0.0085	280	brittle fracture

Metallographic examinations

To estimate the influence of microstructure on brittle fracture of cast steel, the following observations have been made:

- microstructure examination on light microscope
- fracture surface analysis on scanning microscope
- precipitates identification on replicas and thin foils

The tested cast steel was a ferritic-pearlitic grade with uniformly distributed pearlitic and ferritic grains. The mean grain size was 17.2 µm.

The scanning microscope examination of fracture surfaces shows that at a temperatures from +20°C to -45°C the ductile fracture took place.In the temperature range from -60°C to -196°C the transgranular brittle fracture has occurred (Figs.1,2).

To estimate the influence of elements of microstructure on failure process, an analysis of the precipitates has been made. It was stated that the precipitates existed in two different shapes: as cementite lamellae (Fig.3) which formed pearlitic colonies and as spheroidal carbides inside ferritic grains (Fig.4).

In Fig.4 the carbides in ferritic matrix and in the grain boundaries are presented. As it can be seen, there are no carbides at the grain boundaries where crack initiation could take place.

Discussion of results

The results of mechanical tests and microscopic examinations have shown that the notched samples below the temperature of -60°C fractured in a brittle way. The mean value of the calculated process zone size was equal to 240 μm and was independent of temperature as long as the fracture was brittle. The calculated process zone size includes about 16 grain diameters and is rather large. When the fracture was ductile (from +20 to -45°C) the process zone size was in the range of 500 -600 μm and depended slightly on temperatures. Microscopic examinations indicated the absence of carbides at the grain boundaries where the process of steel cracking usually starts. Therefore the brittle failure was initiated either in pearlitic or ferritic grains. The cleavage fracture process in fully pearlitic steel was investigated in (6) and (7) using the same Griffith-Owen method. According to these papers the critical stress of fracture in pearlite is equal to ~2000 MPa and is considerably higher in comparison with the critical stress in tested material. Thus, it seems that failure starts within ferritic grains. To check if carbides within the ferritic grains can initiate the process of brittle fracture, the stress necessary to propagate crack of the dimension equal to the carbide diameter was calculated using Griffith formula as follows :

$$\sigma = \sqrt{\frac{2E\gamma}{\pi a(1-\nu^2)}} \tag{3}$$

where : E - Young's modulus ($2*10^5$ MPa)

γ - surface energy ($\gamma = 1.7$ J/m^2)

ν - Poisson ratio ($\nu = 0.3$)

a - crack size equal to a half of carbide diameter ($a = 10^{-7}$ m)

The calculated stress determined from eq.(3) is equal to 1542 MPa and is close to the experimentally determined mean values of stress of the brittle fracture equal to 1475MPa. The above data suggest that cracking of carbides inside ferritic grains may initiate the cleavage fracture of the tested cast steel.

Conclusions

1. In the tested cast steel the brittle fracture occurred when the stress level of 1475MPa was exceeded over a distance of 240 μm ahead of the crack tip.
2. For the tested cast steel there is an agreement between Griffith stress calculated for a crack size equal to the carbide precipitates diameter and the stress experimentally determined. This suggests that the brittle fracture of the tested cast steel is initiated by cracking of the spheroidal carbides situated inside ferritic grains.

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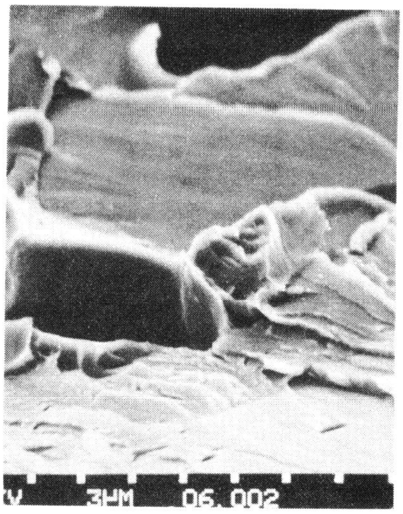

Figure 1 Cleavage fracture at -60°C

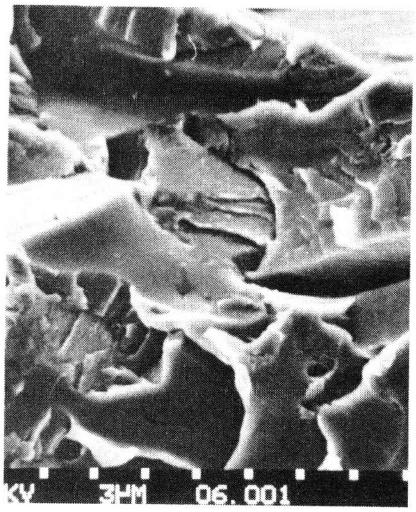

Figure 2 Cleavage fracture at -196°C

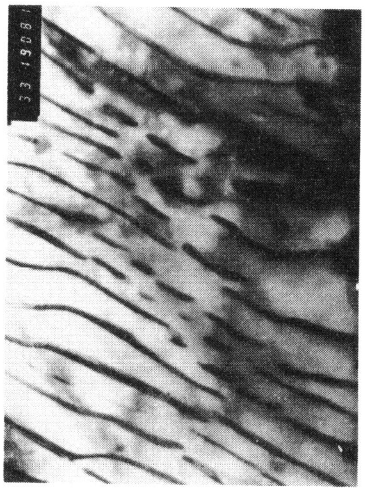

Figure 3 The lamellae of cementite in pearlite

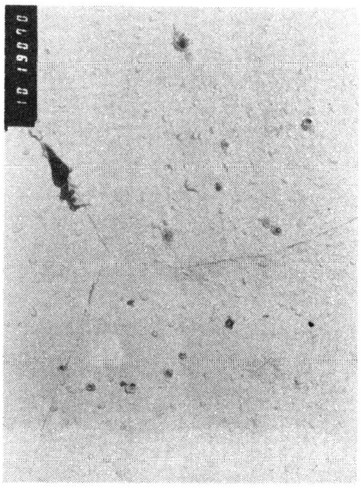

Figure 4 The carbides in ferritic matrix