THE APPLICATION OF A LOCAL APPROACH TO INTERGRANULAR BRITTLE FRACTURE OF LOW ALLOY STEELS

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The local criterion of cleavage fracture derived by Beremin was used in the case of intergranular brittle fracture (IBF). Its application leads to a Weibull modulus of 9 and a clear non linearity in the Weibull plot. Within a first approximation, the observed non linearity of the results may be interpreted as a bilinearity implied by two concurrent distributions with independent statistical parameters. Each individual distribution is found to be a two parameters Weibull distribution. Using statistical values of each population the temperature dependence of fracture toughness is predicted. A new bimodal local fracture criterion is derived for IBF. This criterion could be applied in the case of mixed, cleavage + intergranular fracture (MCIF).

1. INTRODUCTION

An important source of scatter in the fracture toughness properties of heavy forgings in Mn Ni Mo low alloy steel has been recently attributed to the presence of small areas of weak toughness microstructures located near the notch tip of the Charpy V specimens. In fact segregation of impurities (P,S...) to grain boundaries during heat treatments of low alloy steels may induce intergranular fracture, in local brittle zones (ghost lines), leading to low values of Charpy V impact properties and of fracture toughness (K_{IC})[1].

The aim of several studies on this problem is to determine by the local approach of fracture how this population of brittle zones (weakest links) can affect the parameters of the Weibull statistics used for modelling the brittle failure probability.

In the present work, the Beremin local approach, initially proposed for cleavage fracture, is applied to the case of pure intergranular brittle fracture in a special heat treated material.

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Application of the model in structural steels which present strongly segregated zones and a mixed, cleavage + intergranular (MCIF) mode of fracture was also investigated.

2. MATERIALS

A)Pure intergranular brittle fracture:

In order to produce IBF, an A 533 type steel with a phosphorus content of 170 ppm was thermally embrittled. Step cooling heat treatment was used to promote intergranular segregation as indicated in ref [2]. The resulting microstructure is similar to that found in some strongly segregated ghost lines of heavy forgings.

B) Mixed, cleavage and intergranular fracture:

This type of fracture was observed in segregated zones (ghost lines) of a SA 508Cl3 type steel issued from one nozzle cut-out of a 900 MW Standard Unit of a PWR.

3. THE BEREMIN MODEL

The Beremin model for brittle fracture of low alloy steels [3] is based on the critical stress concept and on the assumption of a certain statistical distribution of the size of the defects at the origin of the fracture. Using the weakest link theory and the fact that cleavage failure cannot occur without any plasticity, it is possible to express the probability of failure Pr of a structure having a plastified volume Vp in a form similar of those proposed by Weibull [4]:

$$P_r = 1 - \exp\left(-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right) \qquad (1)$$

where

$$\sigma_w^m = \int_{V_p} \sigma_I^m \cdot \frac{dV}{V_o} \qquad (2)$$

σ_w is named the Weibull stress.

σ_u is the value of σ_w for a probability of failure of 0.63.

m is a measurement of the scatter of σ_w. In theory, it depends only on the distribution of the defects size[5].

σ_I is the maximum principal stress in the volume dV.

V_o is a volume, characteristic of the material, which has to be large enough to contain several defects and small enough to be considered as uniformely loaded in any case of stress distribution.

To obtain the parameters of the model m and σu for a given material, tests and elastoplastic finite element computations of notched tension specimens have to be performed.

4. EXPERIMENTAL RESULTS

A)Intergranular Brittle Fracture

To apply the Beremin local approach to IBF, 32 notched tension specimens were tested between liquid nitrogen temperature and -90 °C. All these specimens were cut in the transverse direction of the plate. After each test, the specimens were examined in S.E.M and pure intergranular fracture was found for all them.

B)Mixed (Cleavage + Intergranular Fracture)

For segregated material (containing ghost lines), 32 notched tensile specimens in longitudinal and radial orientations were tested at -80°C and -40°C. Mixed rupture with cleavage and intergranular appearance were observed by S.E.M examinations only for 11 specimens.

5. LOCAL APPROACH APPLICATION TO IBF

Using finite elements computations, the parameters of the Beremin criterion are determined. The parameters m and σu are found to be respectively equal to 9.18 and 3610 MPa for $V_o=(200\mu m)^3$ (Figure 1). But it is clear that the correlation of the linear regression in the Weibull plot is rather poor because of the quasi bilinear behaviour. The original Beremin model do not describe the set of data in a satisfactory way. So it seems necessary to develop a new model in order to describe the IBF.

6. A PROPOSED LOCAL CRITERION FOR IBF

Let us consider a component which has two independent modes of intergranular failure, A and B. For each mode we associate a probability of failure P_A and P_B. P_A is the probability of failure if mode A is present alone and P_B is the probability of failure if mode B is present alone.

The probability of non-failure of a component is then the product of the two individual probabilities of non-failure [6],[7]

$$1-P_T= (1-P_A)*(1-P_B) \quad (3)$$

If each mode of failure obeys the two-parameter Weibull distribution, then equations 1 and 3 yield

$$P_T=1-\exp\left(-\left(\frac{\sigma_w}{S_{uA}}\right)^{m_A}-\left(\frac{\sigma_w}{S_{uB}}\right)^{m_B}\right) \quad (4)$$

This failure probability function contains four adjustable parameters, m_A, m_B, S_{uA}, S_{uB}. But the estimation of the parameters m_A end m_B from the application of the two-parameters Weibull distribution separately allows us to adjust only the parametres S_{uA} and S_{uB}.
The application of two-parameters Weibull distribution in each population separately gives, for $Vo= (200\mu m)^3$:
For population A: $m_A=49.34$, $\sigma_{uA}=2002$ MPa
For population B : $m_B= 8.23$, $\sigma_{uB}=2959$ MPa
Using the statistical parameters of individual populations A and B, the fracture toughness can be predicted when the stress strain distribution ahead of the crack tip is known [3]. Theoretical prediction of temperature dependent fracture toughness, with the parameters of A and B population, for a probability of fracture of 5% and 95%, is given in Figure 2.
In relation 4, we associate a Weibull stress (σw) with a certain probability of failure. This Weibull stress is strongly dependent of m (equation 2). The estimation of the Weibull stress can therefore be performed with m obtained when we consider the two parameters Weibull distribution for all the experimental data (m=9.18). The new local criterion for intergranular fracture can be written:

$$P_T=1-\exp\left(-\left(\frac{\sigma_w(m)}{S_{uA}}\right)^{m_A}-\left(\frac{\sigma_w(m)}{S_{uB}}\right)^{m_B}\right) \qquad (5)$$

with

$$\sigma_w(m)=\sqrt[m]{\int_{V_p}\sigma_1^m\frac{dV}{Vo}} \qquad (6)$$

Experimental data are plotted with equation 5 in Figure 3. In the same figure the two parameters Weibull distribution is reported (equation 1).

7. APPLICATION IN MCI FRACTURE

The proposed criterion can be used to predict fracture in the case of MCIF. The application of Beremin approach in specimens containing segregated zones leads to values of statistical parameters, similar to these of pure IBF, m=10.77, and the same bilinearity. Experimental data and theoretical predictions with equation 5 are given in Figure 4.

8. CONCLUSIONS

The application of Beremin model to intergranular fracture leads to a low value of Weibull modulus indicating a large scatter in the results associated with poor fit of the data. Further analysis of results can be interpreted by two concurrent distributions of results with independent statistical parameters. Each individual distribution is found to be a two-parameters Weibull distribution. Prediction of fracture toughness as a function of temperature can be done by using the statistical parameters of each population.

A new bimodal local fracture criterion was derived for intergranular fracture. It could be applied in the case of mixed (cleavage + intergranular) fracture: In this case the intergranular fracture mode would determine the critical stress and its scatter.

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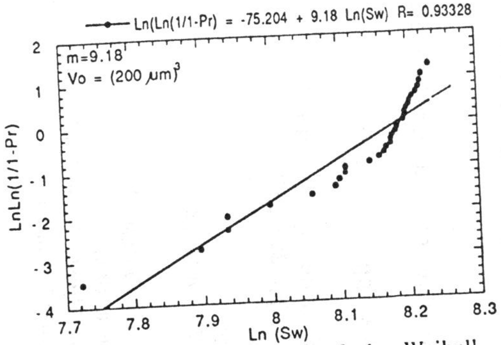

Figure 1: Determination of the Weibull parameters in the case of IBF

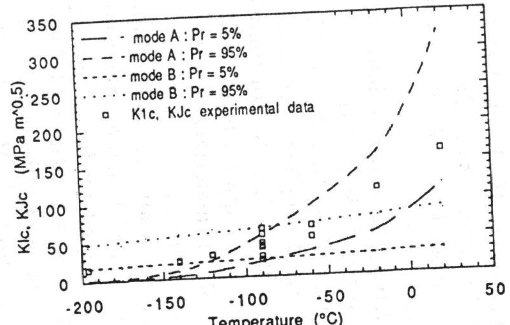

Figure 2: Prediction of fracture toughness from statistical parameters of two populations

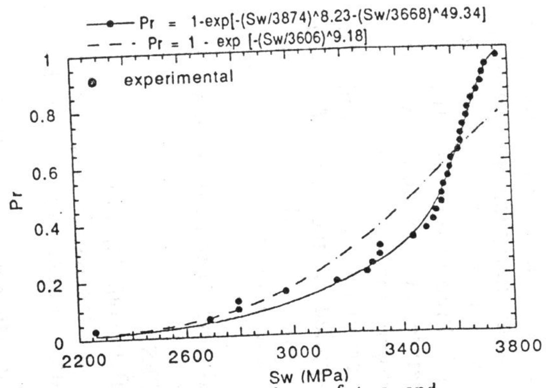

Figure 3 : Comparaison of two and four parameters Weibull Statistics

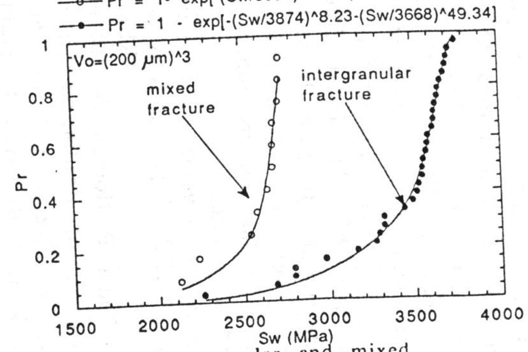

Figure 4: Intergranular and mixed fracture data fitted with equation 6