ON THE CORRELATION BETWEEN THE J-INTEGRAL AND THE CRACK TIP FINITE DEFORMATION

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ABSTRACT

The Large Strain Zone (LSZ) produced at the crack tip under mode I loading has been the subject of numerous theoretical studies, both analytical and numerical. Most of them are intended to determine the stress and strain fields at the LSZ as a function of a loading parameter (stress intensity factor, J integral, CTOD), while at the same time estimating the LSZ size. In this paper some experimental results of the LSZ length over the crack plane, x_{LSZ}, are presented, together with the J-integral values corresponding to the measured LSZs. Experimental measurements were made on a ferritic-pearlitic steel that fails by cleavage, without any previous ductile tearing, at room temperature. One of the special features of this is that the process of void nucleation and growth in the LSZ produces a ductile morphology, which contrasts with the brittle appearance of the remaining fracture surface. This allows the LSZ size to be experimentally evaluated from fractographic measurements performed with a scanning electron microscope, so that each value is associated with the one corresponding to the J-integral at fracture. As a consequence of the statistical nature of the cleavage failure, the J-integral and the LSZ size reached before failure are very different from one test to another and both spread over a broad range of values. This provides an empirical correlation between J and x_{LSZ}, that is shown to be in agreement with the theoretical predictions available in the literature.

INTRODUCTION

The Large Strain Zone (LSZ) produced at the crack tip under mode I loading has been the subject of numerous theoretical studies, both analytical and numerical [1, 2]. Most of them are intended to determine the stress and strain fields at the LSZ as a function of the loading parameter (stress intensity factor, J integral, CTOD) dominating these fields around the LSZ, while at the same time estimating its size. According to Rice and Johnson [1], the length of the LSZ ahead of the crack tip is roughly twice the CTOD value, when referred to the non-deformed configuration of the crack.

The aim of this paper is to validate experimentally the theoretical estimations of the LSZ length. An extensive fracture test program was carried out to measure both magnitudes, the LSZ length and the J-integral at fracture, in precracked samples of a structural ferritic-pearlitic steel. The J-integral was determined from the load versus displacement curves according to standardised methods [3], whereas the LSZ length was measured on the fracture surfaces with a scanning electron microscope.

MATERIAL

The material investigated is a low carbon steel. The chemical composition measured by GDL emission spectroscopy is shown in Table 1.

TABLE 1
CHEMICAL COMPOSITION OF THE TESTED STEEL (WEIGHT %)

C	Mn	Si	Cr	V	Ni	P	S
0.20	1.14	0.21	0.18	0.08	0.07	0.006	0.001

It is a hypoeutectoid steel with a ferritic-pearlitic microstructure, formed by pearlitic colonies within a proeutectoid ferritic matrix, as shown in Fig. 1. The clear zones correspond to the ferritic matrix and the dark ones are the pearlitic colonies, most of which are homogeneously distributed within the ferritic matrix although coarse aggregates are sometimes found.

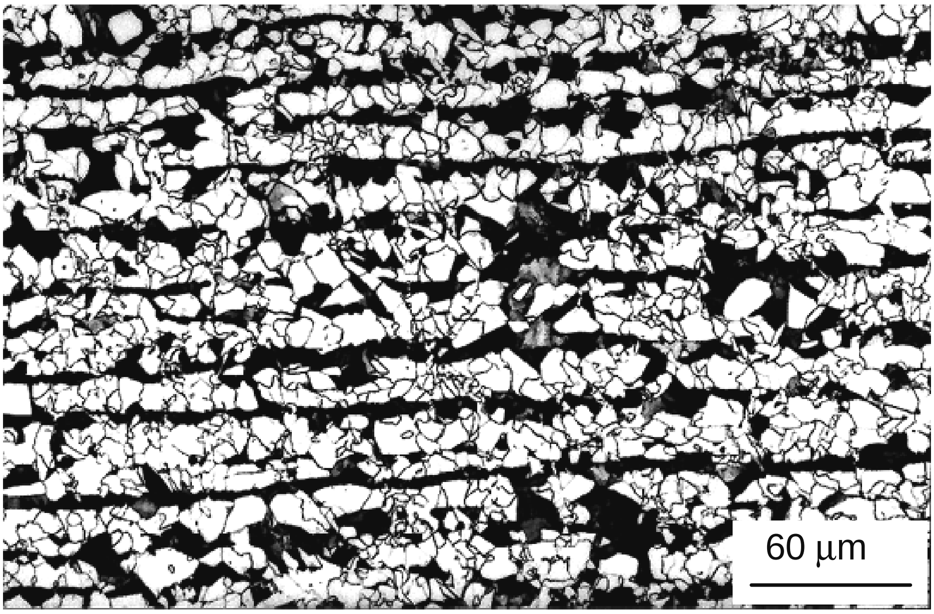

Figure 1: Ferritic-pearlitic microstructure of the investigated low carbon steel

The mechanical properties at room temperature, measured by tensile testing, are given in Table 2.

TABLE 2
MECHANICAL PROPERTIES OF THE MATERIAL

Elastic modulus E (GPa)	Yield Strength $R_{p0.2}$ (MPa)	Tensile Strength R_m (MPa)	Maximum uniform elongation, ε_u (%)	Stress-strain curve (Ramberg-Osgood)
200	500	710	11	$\varepsilon = \frac{\sigma}{E} + \alpha \frac{R_{p0.2}}{E} \left(\frac{\sigma}{R_{p0.2}} \right)^n$ $\alpha = 2.1$ $n = 6.5$

FRACTURE TESTING

Standard compact tension specimens 12.5 mm thick were fatigue precracked until the ligament was reduced to 10 mm. After precracking, the samples were side-grooved up to a thickness reduction of 20%. Load-line displacement –the crack opening displacement measured at the load line by a COD clip gauge– was monitored and employed as the control variable in the tests. Testing was carried out at 20°C with a constant load-line displacement rate of 0.1 mm/min until fracture, following the recommendations of ASTM E813 standard [3].

In all of the fourteen tests, fracture was brittle, with no ductile tearing. Fig. 2 shows two extreme cases, when fracture took place almost in the elastic part of the load versus load-line displacement curve, and when fracture occurred long after the sample was in the fully yielding condition.

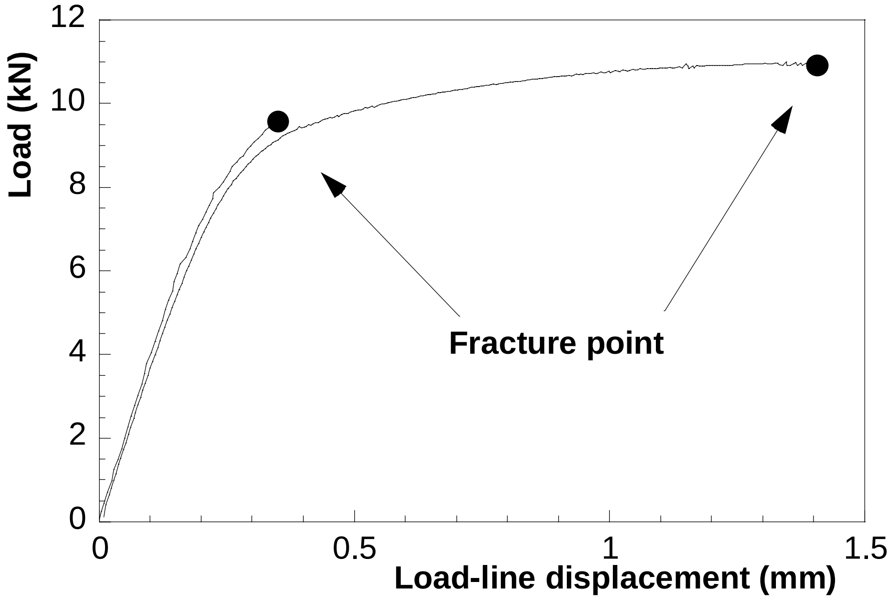

Figure 2: Load versus load-line displacement curves obtained in two fracture tests.

FRACTOGRAPHY

The fracture surface of the samples showed three different regions, as Figs. 3 and 4 illustrate. The first zone from left to right, the fatigue precrack, shows the typical features of the fatigue process, which are periodically repeated along the crack growth direction. The second zone, on the contrary, exhibits a ductile morphology and contains some areas covered with numerous holes (of a typical diameter around 20 to 40 μm) that appear to have suffered severe plastic deformation (Fig. 3). Within some of the holes, smaller spherical particles (diameter around 5-10 μm) are sometimes found. The third zone (shown in Fig. 4) corresponds to the final fracture and presents the typical cleavage pattern, with flat facets separated by cleavage steps.

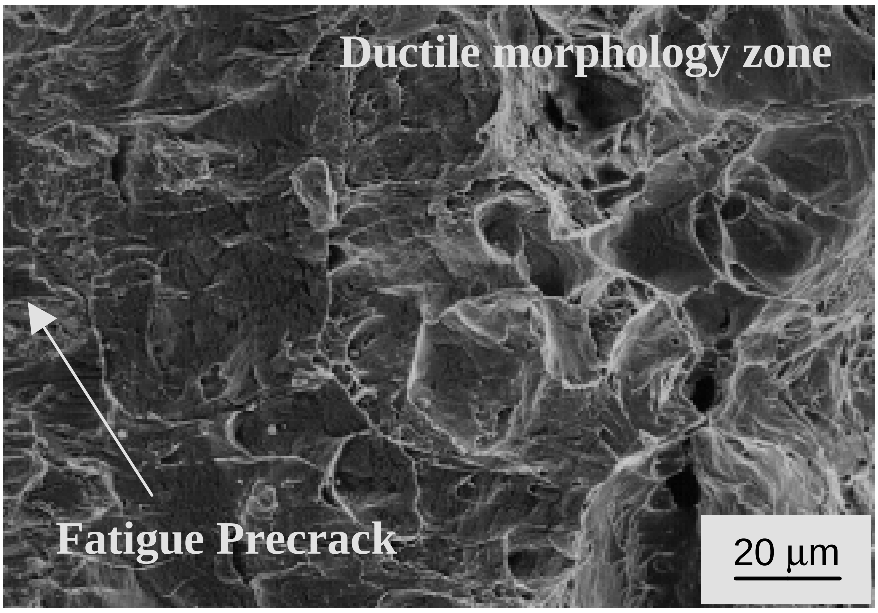

Figure 3: The fatigue precrack (at the left) and the ductile morphology zones (at the right).

The fractographic observations revealed that the size of the ductile morphology zone (from now on DMZ) was dependent on the plastic deformation level attained in the test. Consequently, the length of the DMZ was carefully measured on the fracture surfaces with a scanning electron microscope (resolution was better than 2 μm) and compared to the J-integral value as determined from the load-load line displacement curve, following the ASTM E813 standard. In Table 3, the length of the DMZ and the corresponding J-integral value are presented for the fourteen tests. Each DMZ length is an average of nine different measurements equally spaced along the thickness of the broken sample.

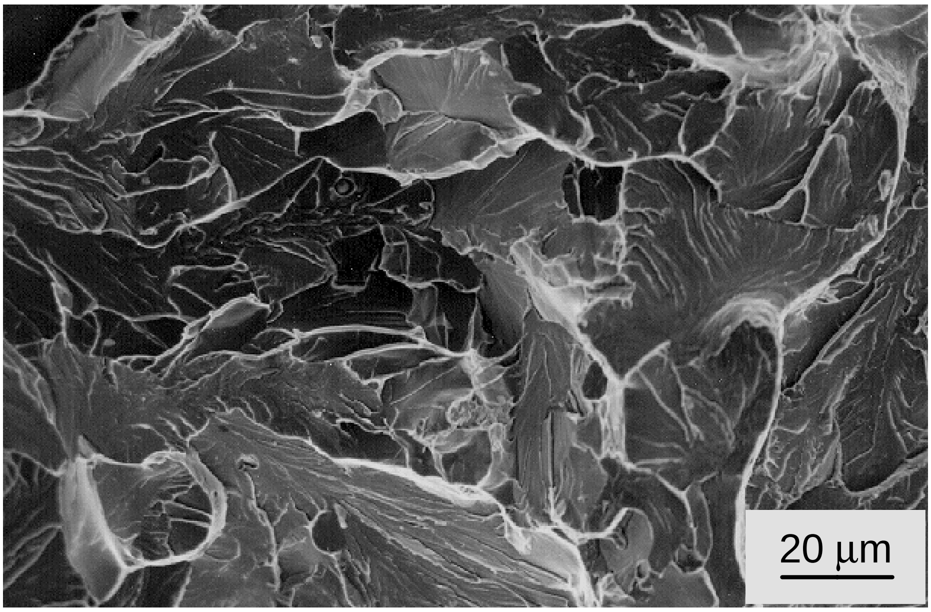

Figure 4: The final fracture zone showing a typical cleavage pattern

TABLE 3
J-INTEGRAL VALUES AND CORRESPONDING LENGTH OF THE DMZ

J (kJ/m^2)	8.3	10.0	17.7	18.9	66.1	108.4	123.9	130.0	171.7	215.3	225.0	237.5	253.2	291.4
DMZ (μm)	38	32	16	24	74	94	130	142	200	260	266	320	358	392

The J-integral values are fairly dispersed, as expected from the variability in the load versus displacement curves, but it is significant that this also occurs with the DMZ measurements.

DISCUSSION

As mentioned earlier, fracture occurred by a sudden cleavage process with no previous ductile tearing. The statistical nature of cleavage failure causes a remarkable variability in the plastic deformation level attained in the tests, which explains the observed dispersion in J-integral values. However, the parallel trends shown by the two types of results given by Table 3 seem to indicate that the J-integral value and the length of the DMZ are correlated. The most promising explanation is that the DMZ represents the large strain zone at the crack tip, whose size is determined by the J-integral value when the load process is J-controlled.

Obviously, the overall plastic zone ahead of the crack tip cannot be identified with the DMZ in the specimens that failed after extended yielding, but a simple quantitative verification allows this identification to be discarded in the remaining cases. For small scale yielding, the size r_y of the plastic zone ahead of the crack tip is well known and can be calculated from the J-integral, the elastic modulus E, and the yield strength $R_{p0.2}$ (see [4], for instance):

$$r_y = 0.04 \frac{J E}{R_{p0.2}^2} \tag{1}$$

Beyond small scale yielding, the values calculated with this formula are a lower bound of the plastic zone size, in spite of which they are much higher than the measured DMZ lengths. Indeed, the values obtained by dividing the DMZ row of Table 3 by the J-integral row are at least one order of magnitude lower than the ratio $r_y / J = 0.04\ E / R^2_{p0.2} = 0.032\ MPa^{-1}$ provided by Eq. (1).

The other possibility (the identity between the LSZ and the DMZ) can be checked by comparing the experimental DMZ measurements with the theoretical predictions of Rice and Johnson [1] for the large strain zone. In accordance with them, the LSZ extends ahead of the crack tip over the material that occupies a length X_{LSZ} approximately twice the CTOD in the non-deformed configuration of the cracked body. Therefore X_{LSZ} • 2δ, δ being the value of the CTOD. However, the experimental measurements on the fracture surfaces are taken over deformed material. Then, it is mandatory to calculate the LSZ size in deformed material, x_{LSZ}, in order to compare it with the DMZ values. The relationship between the distances of a material point ahead of the crack tip before and after deformation was calculated by Gutiérrez-Solana et al. [5] from the results of Rice and Johnson [1]. According to this relation a material length 2δ ahead of the non-deformed crack tip becomes reduced to 1.4 δ in the deformed crack tip, and consequently x_{LSZ} • 14 δ.

When the J-integral dominates the crack tip region through the HRR fields [6,7], the CTOD is given by [2]:

$$\delta = \frac{d_n J}{R_{p0.2}} \tag{2}$$

where d_n is a non-dimensional constant depending on the tensile properties described in the terms of Table 2. The standard EFAM GTP94 [8] provides data in the Appendix 7 from which the following expression of d_n can be derived:

$$d_n = \left(0.787 + \frac{1.554}{n} - \frac{2.45}{n^2} + \frac{16.952}{n^3} - \frac{38.206}{n^4} + \frac{33.13}{n^5}\right)\left(\frac{\alpha R_{p0.2}}{E}\right)^{1/n} \tag{3}$$

For the values given in Table 2, the value of d_n is 0.45 and then:

$$x_{LSZ} = 1.4\,\delta = 1.4\,\frac{0.45 J}{R_{p0.2}} = 0.63\,\frac{J}{R_{p0.2}} \tag{4}$$

The measured length of the DMZ is plotted against $J/R_{p0.2}$ in Fig. 5 along with the straight line defined by Eq. (4). It is seen that the experimental data gather round the theoretical prediction, which indicates that the DMZ is actually the LSZ and the tested steel allows it to be measured by fractographic techniques. The region of J-dominance can be calculated following the standard ASTM E813 [3]; since the uncracked ligament b and the specimen thickness B were of equal length (b=B=10 mm) in the fourteen tests, and since $R_m = 1.42\ R_{p0.2}$ for the tested steel:

$$b > 50 \frac{J}{R_{p0.2} + R_m} \Rightarrow \frac{J}{R_{p0.2}} < 0.048\, b \tag{5}$$

As depicted in Fig. 5, the vast majority of the experimental data remain below the limit J value given by Eq. (5), so fracture takes place under J-dominance conditions and the CTOD expression in Eq. (2) is adequately employed.

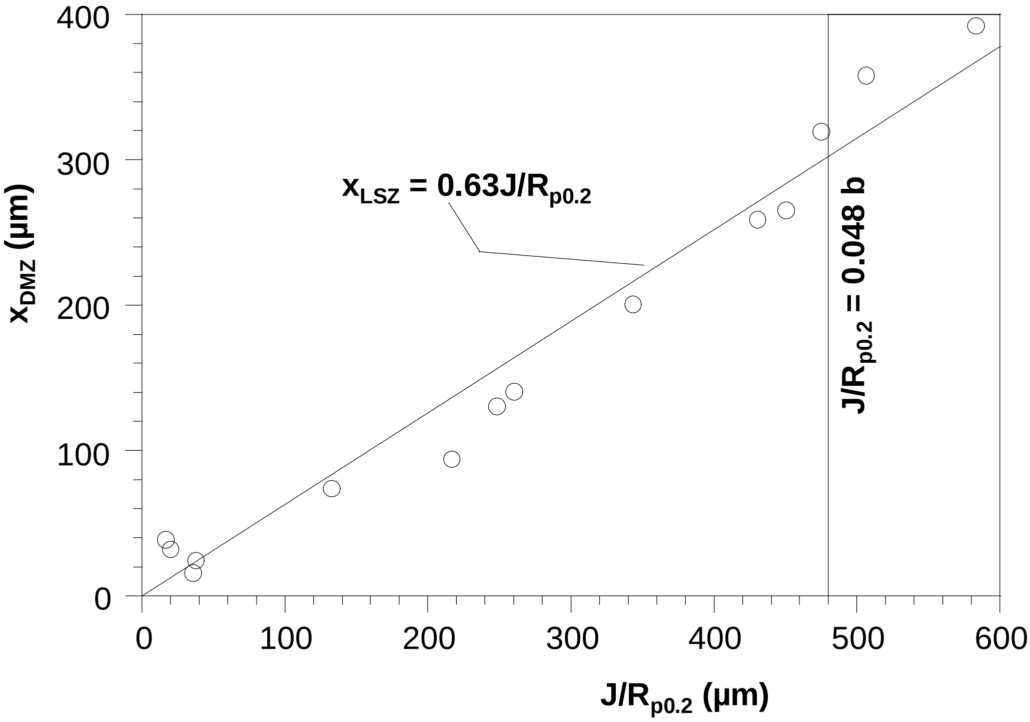

Figure 5: Comparison of the measured length of the ductile morphology zone (x_{DMZ}) and the theoretical length of the large strain zone (x_{LSZ}).

CONCLUSIONS

The Large Strain Zone (LSZ) ahead of the crack tip was measured by fractographic techniques as a function of the J integral. The material employed is a ferritic-pearlitic steel, which fails by cleavage with no previous ductile tearing at room temperature. The great plastic deformations within the LSZ promote the nucleation and growth of numerous holes, and as a consequence the resulting fracture surface has a ductile morphology which clearly differs from the cleavage pattern of the final brittle fracture. The length of this fibrous area was measured on the fracture surface and agrees with the theoretical predictions of the LSZ size.

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