A PROPOSAL FOR A MICROSTRUCTURALLY BASED J_{Ic} DETERMINATION

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Analyses of existing Standards for the determination of fracture toughness of ductile materials, namely ASTM E 813 and EGF P1 have allowed to identify that the adopted engineering estimates of this property show a low degree of correlation with the material microstructure. A physical model for the blunting of a fatigue precrack and for the early stages of stable crack propagation has allowed to propose a new procedure that relates the determination method more strictly to the material characteristics.

INTRODUCTION

In recent years a global movement has arisen to review or set the Standard test methods for the determination of fracture toughness, J_{Ic}, identified by ASTM E 813 as "an engineering estimate of fracture toughness near the initiation of slow stable crack growth for metallic materials". A major review of the ASTM Standard appeared in 1987 (1). A new proposal for determining the fracture resistance of ductile materials has been quite recently released with the designation EGF P1-90 (2), under the impulse of a Working Party created within the EGF Task Group I on Elastic Plastic Fracture Mechanics (3).

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CRITICAL ANALYSIS OF EXISTING STANDARDS

The ASTM Standard identifies J_{Ic} as a consequence of computations based on:

i) a mathematical approximation of the fictitious crack advance due to the crack tip blunting (Δa_i);

ii) the determination of J_{Ic} at the intersection, in the J-Δa field, between the J-R curve and the straight line of equation $J = 2\sigma_Y \cdot (\Delta a - 0.2)$ parallel, with an offset of $\Delta a = 0.2$ mm, to the blunting line.

No real correlation exists any more between the J_{Ic} determined in such a way with a physically well established critical event, as it was in the previous Standards, e.g. ASTM E 813-81 (4), mainly because it has been seen very difficult and not reproducible for all the materials to model by a valid mathematical expression the complex deformation process that takes place at the fatigue pre-crack tip from the moment a cracked body is loaded up to the point of onset of stable crack growth. The so called "blunting line" is in fact a gross approximation, as it was a gross approximation to model the stable crack growth with another straight line. In the recent version of the Standard the J-R curve has become indeed an exponential regression. However a certain degree of ambiguity arises from the impossibility to have a clear distinction between J-Δa points deriving from the blunting process and those belonging to the real stable crack advance. The norm that imposes to exclude from the J-R curve experimental points lying on the left of the so-called 0.15 mm offset exclusion line has been dictated by the above described uncertainty. The further use of the 0.2 mm offset line - parallel to the blunting line - should guarantee in an engineering sense that the J_{Ic} value determined with the Standard has a large probability to lie on or very close to the stable crack propagation curve. Yet the real physical event may be at times very displaced.

The same criticism cannot be globally addressed to the EGF Standard. In fact, it is still assumed in the norm that in a test sample subjected to load after fatigue pre-cracking the fictitious crack advance can be modelled geometrically as the projection on the crack advance plane of the intense straining surface generated by the blunting process (critical stretched zone) during the application of a quasi-static load. The width of a such projection can be determined by suitable observations of the fracture surface. Its determination, although difficult and in some cases loaded by errors, should allow to determine which are the points of the J-Δa plot clearly pertaining to each of the two different processes, i.e. blunting and stable crack advance. The EGF Standard identifies the stretched zone width with the (Δa_i) notation and the corresponding applied J-integral with J_i.

However, the above hinted difficulties for the exact determination of Δa_i have led to the insertion in the EGF Standards of engineering approximations deriving from a philosophical approach not very dissimilar from the ASTM one. J values corresponding to 0.2 mm of stable crack growth or 0.2 mm of total crack growth have been introduced and termed $J_{0.2/BL}$ and $J_{0.2}$, respectively. The EGF Standard has an inside superiority in respect to the ASTM Standard deriving from the more punctual mathematical modelling of the blunting process evidenced by the use of the strain hardening exponent in the computation of the blunting line.

Summarizing, both the Standards introduce engineering approximations that can lack at times a sufficient degree of correspondance with the real material properties. The assumption of 0.2 mm of stable crack growth for the identification of the J value to introduce in structural assessments (J_{Ic} or $J_{0.2/BL}$) may lead in some cases to too optimistic or too conservatives results. The other assumption by the EGF Standard of the 0.2 mm total crack growth can be particularly penalizing for the more strain-hardening materials, since no guarantee exists that the blunting process has been completed at this distance. Many investments in production plants to produce cleaner alloys risk not to be taken into due account.

From the above considerations it is possible to infer that more work is needed to single out simpler and more reliable methods for the determination of Δa_i, and hence of J_i (3); it is also important to arrive to a better link between the material properties and the stable crack advance that has to be used in an engineering sense to individuate J_{Ic} on the J-R curve.

NEW PROPOSAL

A series of experimental determinations on ductile fracture in ferritic-pearlitic C-Mn steels as well as in quenched and tempered low alloy steels performed by

Firrao, Roberti et al (5-11) have allowed to establish that in these materials the blunting process is strictly governed by the non-metallic inclusion population; furthermore, it was demonstrated that the crack-tip fictitious crack advance, Δa_i, is constantly equal to the inter-particle spacing between major inclusions, $\underline{s}$. A physical model for the end of the blunting process and the early stages of stable crack advance has also been proposed and proved.

For these materials, characterized by widely differing strain hardening properties, it is therefore possible to define a simple procedure for the determination of the fracture toughness at the onset of the stable crack growth, J_i, based upon a quantitative metallography determination of $\underline{s}$. By substituting such a length into the mathematical formulation that best models the J-R curve a physically based value of J_i can be computed. Moreover, quantitative metallography can be more simply and more reliably automated than scanning electron microscopy. Parameters of the inclusion distribution within an alloy can even be provided by the producer.

If one senses that in the engineering sense J_i is a too conservative measure of the fracture toughness of the material and choses to allow a certain degree of stable crack propagation for the identification of a less conservative critical value of applied J, the same physical model can be used. In fact the earliest stage of crack propagation from a blunted crack corresponds to the plastic collapse of ligaments remaining between pores nucleated around the array of inclusions closer to the blunted tip. Modelling the inclusion population as they were distributed in equally spaced rows, the blunting corresponds to a $\Delta a = \underline{s}$, the end of the first stable advance stage to a $\Delta a = 2\underline{s}$. An engineering value more linked to the material characteristics can be thus obtained.

Figure 1 reports an example of application of the proposed norm to calculate an engineering estimate of the fracture toughness more linked to the material microstructure and therefore termed $J_{Ic,m}$. Experimental data refer to a UNI 39 NiCrMo 3 steel with an average inclusion spacing of 0.29 mm, quenched and tempered at 650 °C. Similar engineering approximations computed by the ASTM E 813-87 and EGF P1-90 Standards (J_{Ic} and $J_{0.2/BL}$) are also indicated in the Figure. Either one of the ASTM or EGF J-R curves can be adopted provided that points positioned at Δa values smaller than s are not taken into account in the computation.

CONCLUSIONS

Actual ASTM and EGF Standards for the determination of the fracture toughness in ductile materials have adopted procedures for its engineering evaluation that are not or not closely related to the physical characteristics of the materials. By the use of a physical model of the blunting process and of the early stage of stable crack propagation from a pre-existing fatigue crack a new proposal has been formulated to individuate both the value of the applied J integral at the end of the blunting stage and the value of J after a microstructurally related degree of crack advance. The latter can be used as an engineering approximation of the fracture toughness in structure assessment procedures.

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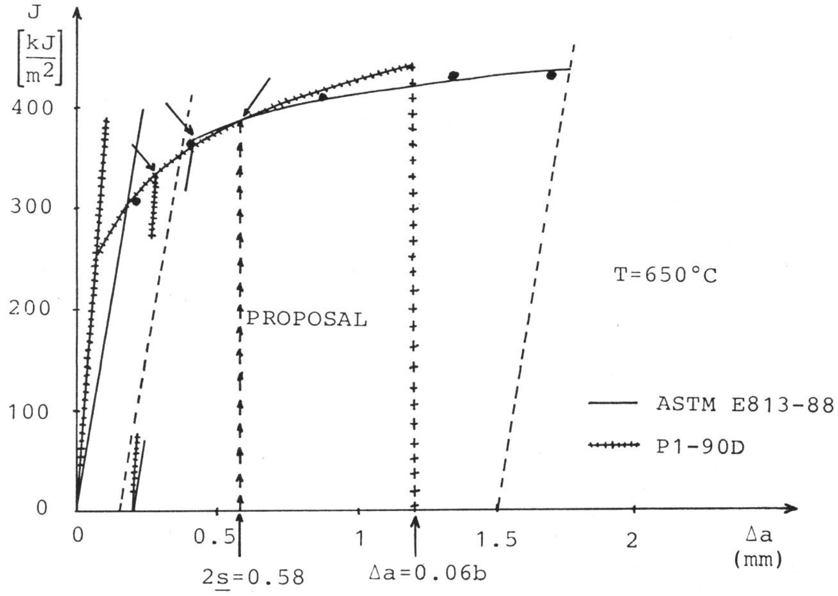

Figure 1 Example of application of the newly proposed procedure for the determination of an engineering estimate of fracture toughness. Arrows indicate ASTM J_{Ic}, EGF $J_{0.2/BL}$, and the now proposed $J_{Ic,m}$.