TOUGHNESS VALUES DISPERSION CORRELATED WITH FRACTURE PATH PROFILOMETRIC ANALYSIS OF GREY CAST IRON

G. Zambelli*, L. Haenny*

The fracture tensile strength of grey cast iron gives a large dispersion of values, due to the brittle behaviour of the material. The study of a continuously solidified grey cast iron, with a heterogeneous microstructure reveals that the fracture strength may be closely well correlated to the initial rigidity. This rigidity is associated with the microcracking state of material, dependant on the graphite morphology. This relationship is verified by a roughness measurement of the fracture surface recorded by a profilometric analysis.

INTRODUCTION

The mechanical behaviour of grey cast iron differs fundamentally from that observed in other engineering metallic alloys. Macroscopically, grey cast iron exhibits a non linear stress-strain relationship and an hysteretical loop is recorded on the cyclic loading of the material.

The fracture strength as measured by a tensile test gives a large scatter due to the inhomogeneity of the microstructure. This scatter can be related to the specific mode of fracture in grey cast iron. Fracture in grey cast iron is induced by a progressive damage of the graphite network (lamellae microcracking) associated with localized plastic strains. The final fracture occurs catastrophically without any macroscopic plastic deformation, thus corresponding to a brittle fracture mode. In order to reduce the scatter of the fracture strength, measurements in brittle and heterogeneous material it is necessary to choose test conditions with lead to a stable fracture process. In the case of grey cast iron, those conditions are obtained by the use of a notched 4-points bend specimen.

The aim of the present study is to obtain a verification of this proposition for the case of a grey cast iron produced by continuous casting, with a markedly heterogeneous microstructure. Based on the idea the fracture path depends directly on the microstructure, a profilometric analysis of the fracture profile obtained by the intersection of the fracture surface and a vertical section was undertaken in an attempt to indirectly characterize the microstructure.

*Department of Material Science, Ecole Polytechnique Fédérale, Lausanne (Switzerland)

EXPERIMENTAL PROCEDURE

Material and specimen preparation

The composition of the alloy was C = 3,45 %; Si = 2,3 %; Mn = 0,67 %; P = 0,11 % and S = 0,11 %. The as-cast microstructure consisted of a mixture of primary pearlitic dendrites and eutectic cells with type A and D graphite. A normalising heat treatment (950 C/1 h)/air cool followed by annealing at 700^{o}C produced a large variation of the pearlite-ferrite ratio in the matrix, leaving the graphite distribution practically unaffected. Loading was performed by an electro-mechanical testing machine with controlled crosshead velocity. In order to achieve a stable crack propagation, a 4-points bending specimen configuration was selected. Load point deflection was measured by an inductive transducer and COD by mean of a clip-on gauge. Fracture surfaces of tensile and notched bend specimens were electroplated with a layer of nickel and cut along a plane parallel to the loading axis.

Fracture profiles were polished and etched so that all microstructural constituants were well resolved as shown in figure 1.

Profilometry

Profilometric analysis is an indirect quantitative fractography technique based on observation of sections through the fracture surface. Conventional roughness parameters have been adopted to describe the complex random fracture path, Zambelli and Haenny (1). Profilometric parameters are : the arithmetic average or centerline average Z_m and the root mean square average RMS (figure 2).

A branching parameter $\bar{C}$ was measured along the fracture path. It is the mean value of the distance between the intersections of graphite lamellae with the fracture profile. The $\bar{C}$ values can give information about the "branching" of the graphite network, defined as a change in the direction along the fracture line.

A computer assisted analysis of the fracture profiles has been performed in order to automatically evaluate the measured statistical parameters. These surface roughness measurement were computed for ten randomly cut profiles for each sample at two magnifications, 750 x and 1'000 x.

Tensile Tests

During tensile testing, a partial load removal was applied. The strain measured during the load inversion had been assumed to be fully elastic so that the initial slope recorded in the stress-strain curve was defined as a real elastic stiffness E'. E' measurements were interpreted in terms of compliance values and a decrease in E' value was associated with an increase of microcracking of the material. For a grey cast iron solidified by continuous casting, the variation in stiffness E' as a function of the progressively increased applied stress σ exhibites three successive stages (figure 3). The first stage has a constant E'_0 value equivalent to the tangent modulus measured at nil stress. The value of stiffness E' decreases proportionally to the applied stress for the second stage in pearlitic cast iron and for the second stage and third stages preceeding fracture in the case of a ferritic cast iron. The amplitude of these stages and their characteristics define a state of degradation which is affected by the properties of the matrix. The initial E'_o value is considered to be representative of the quantity and morphology of the graphite phase, but remains unaffected by the matrix microstructure. Fracture strength and strain appear to be dependant on the initial value of stiffness, E'_o.

Toughness

A procedure for measuring toughness has been suggested, Haenny and Zambelli (2) which accounts for the specific cracking process which occurs in grey cast iron. The calculated stress intensity factor is based on an equivalent crack length which is determined by compliance measurements. Change is the microstructure from one specimen to another is taken into account by calibrating the initial elastic stiffness of the specimen E'_g.

Assuming that the initial E'_g value is a material constant property, an equivalent crack length (a_{eq}) may be calculated by means of the corresponding calibration curve. Using a_{eq} values, an equivalent stress intensity factor (K_{eq}) is then calculated.

The analysis of the toughness of the grey cast iron is obtained by accounting for the instantaneous crack length i.e. by determining the R-curves of the tested specimens.

Critical toughness values exhibit a relatively low scatter. Furthermore by a detailed analysis of the results, it is shwon that K_{eq} values are fairly well correlated with the initial elastic stiffness E'_g (figure 4).

RESULTS AND DISCUSSION

The discussion of results concerns only the fracture behaviour of ferritic cast iron. The macroscopical analysis of the fracture profiles of tensile specimens reveals that fracture propagates preferentially through the lamellar graphitic network. Therefore, the fracture profile parameters give more information about zones of weakness in the microstructure. Figure 5 shows the relationship between the initial stiffness E'_o and the standard deviation RMS measured on the profile of ferritic grey cast iron. For the selected magnification, the RMS parameter is not influenced by the dendritic distribution. A correlation was observed between the increase in RMS values, as measured on the fracture profile, and the decrease in initial sitffness E'_o.

A low RMS value is typically associated to type D graphite morphology as observed along the fracture path. While large RMS value corresponds to type A graphite network. Therefore, it is concluded that the RMS parameter is a representative measure of graphite morphology involved in fracture processes.

For the ferritic cast iron specimens (figure 3), the mean value of the fracture strength $\bar{\sigma}_R$ = 150 ± 50 MPa, gave a relative dispersion of 33,3 %. Therefore, the tensile strength values exhibited a very large scatter band. Any attempt to correlate the proposed microstructure parameter (RMS) with fracture strength would be not realistic and have a very uncertain significance.

The second "roughness" parameter, the graphite branching mean value $\bar{C}$ in figure 5, shows a correspondant value with the RMS parameter for high stiffness (type D graphite) and twice the value with regard to the RMS for low stiffness (type A graphite).

This behaviour corresponds probably to a change of the interconnection conditions inside the graphitic network. But a direct correlation between the branching parameter $\bar{C}$ and the size and morphology of graphitic lamellae is not easy to establish because meaningful measure of the microstructural parameter must be found.

For a constant rigidity value E', the following results are obtained for the critical equivalent toughness (K_{eq}) based on elastic compliance measurements and accounting for the initial elastic stiffness E'_g of each tested specimen : $K_{eqc} = 13,9 \pm 0,9$ MPa√m for the ferritic matrix, with a relative scatter of 6 % (figure 4).

Profilometric analysis obtained from the fracture profiles of corresponding bend specimens given, do not significative RMS values changes in relation with the variation of initial stiffness (figure 6).

In figure 4, it is observed that low values of the initial elastic stiffness which have been related to a high initial amount of cracking due to the graphite morphology are associated with low toughness values. This observation appears logical when it is remember that K_{eq} has been interpreted as corresponding to the fracture initiation process which is essentially dependant on microcracking. The constant mean value RMS ≅ 16 µm ± 6 µm corresponds to the type A graphite microstructure observed close to the fracture profiles. The mean branching parameter $\bar{C}$ also remains constant ($\bar{C}$ = 30 ± 10 µm) with regard to the initial stiffness E'_g. This value confirms the presence of a type A graphite microstructure along the fracture path since it is similar to the $\bar{C}$ value measured in the tensile tests for specimens with low stiffness (figure 5). The scatter band of stiffness deviation E'_g for toughness tests (figure 6) is of the same amplitude as that observed in the E' values for tensile tests (figure 5).

The constant RMS value measured shows that microstructural parameters cannot be correlated with the initial elastic stiffness E'_g. This E'_g value essentially represents the stiffness at the head of the notch in a bend specimen while the RMS value is measured on the fracture profile, ahead of the notch. The conditions of fracture during testing involve a preferential crack propagation along a microstructural path of poor strength. This is confirmed by a tendancy for the crack to growth in zones of type A graphite, keeping a constant value for the measured RMS parameter, which is dependant on the microstructure.

The toughness parameter K_{eq}, being representative of the initiation toughness at the head of a notch, can be related to the initial stiffness E'_g. Therefore, no correlation exist between the toughness K_{eq} and the RMS microstructural parameter.

The decrease observed in the scatter of results for the measurements of specific toughness, which characterizes the fracture behaviour of continuously solidified grey cast iron, is probably due to the material having a critical crack length greater than the parameter size which describes the heterogeneity of the cast iron. In the tensile test, the critical crack length size is certainly smaller than the size parameter for a heterogeneous microstructure.

CONCLUSIONS

Since continuously solidified grey cast iron is a brittle material, its fracture behaviour must be characterized by means of a toughness parameter, in order to avoid the large scatter of fracture tensile strength results associated with brittle material. By definition, a toughness measurement is valid only during a stable and limited increase of cracking. This condition is achieved in a bend notch specimen test while the classical tensile specimen test produces instable crack propagation.

The profilometric measurement of fracture paths has been used to characterize the heterogeneous microstructure. This microstructural parameter has been correlated with fracture strength measurements in tensile tests and with critical equivalent initial toughness measurements in 4-points bend tests in order to explain the variation in the relative scatter of results. The following conclusions can be drawn;

- RMS values obtained from the fracture surface of tensile specimens are correlated with the initial stiffness E'. This stiffness depends on the microstructure : an increase in RMS indicates a decrease in the stiffness which defines the initial state of microcracking in the graphitic network.
- A correlation between RMS parameter and fracture strength value in tension is not possible due to the large scatter of the results (± 33 %).
- Critical equivalent initial toughness K_{eq} measurements result in a smaller scatter of the date (± 6 %). These K_{eq} measurements represent the fracture behaviour at the head of the notch and cannot be correlated with the RMS parameter.

A decrease in the measurement scatter which characterize the fracture behaviour of continuously solidified grey cast iron has been obtained by the choice of a toughness test in which the critical crack size is larger than the parameters describing the heterogeneity of the microstructure. The critical equivalent initial toughness parameter K_{eq} is well adapted to the measurement of the fracture behaviour of grey cast iron.

ACKNOWLEDGEMENTS

The authors wish to thank B. Senior, Interdepartmental Institut of Metallurgy and J.F. Urwyler for their contributions to the experimental part of this work. The financial support of the Swiss National Science Foundation within the framework of the national research programme Raw materials and materials problems' is greatly appreciated.

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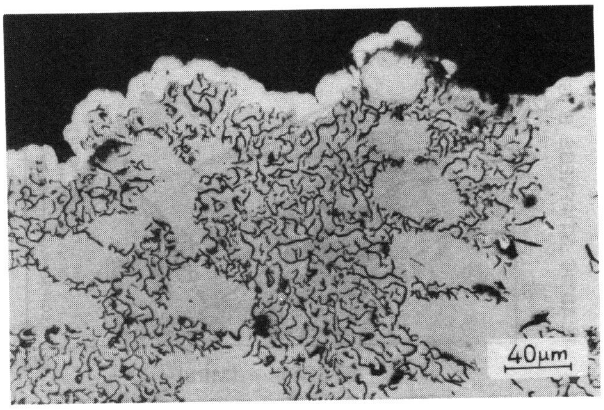

Figure 1 Cross sectional profile of a fracture path in continuously solidified grey cast iron with eutectic type D graphite cells and ferritic dendrites.

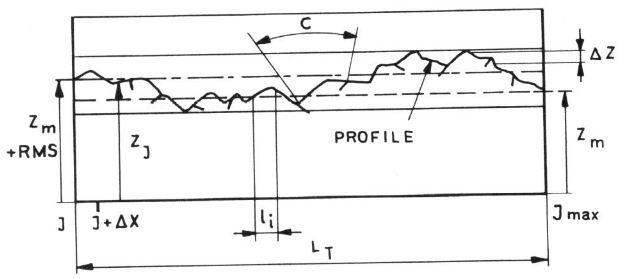

Figure 2 Profilometric parameters used to characterize the profile fracture.

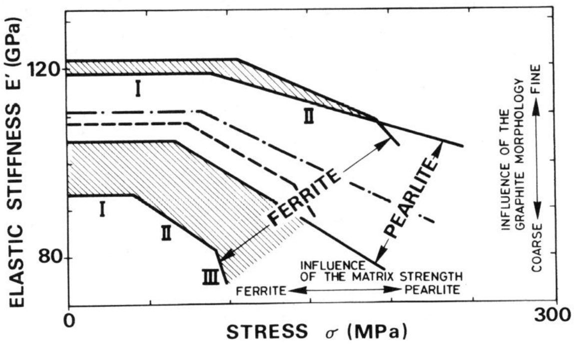

Figure 3 Measured elastic stiffness E' plotted against the applied stress σ in tensile tests for all specimens.

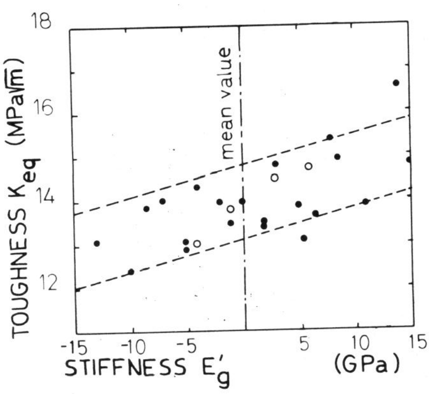

Figure 4 Critical equivalent toughness, K_{eq} correlated with initial elastic stiffne-s E'_g in regard to the mean value $\bar{E}'_g$

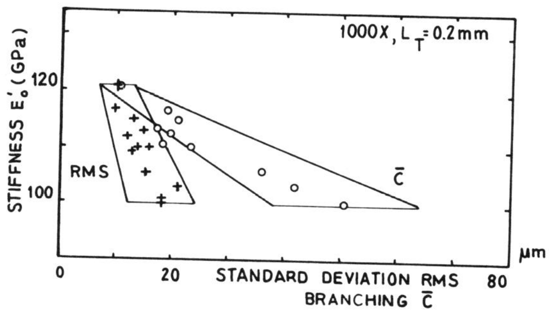

Figure 5 Profilometric standard deviation RMS and mean branching parameter $\bar{C}$ against initial stiffness E'_o

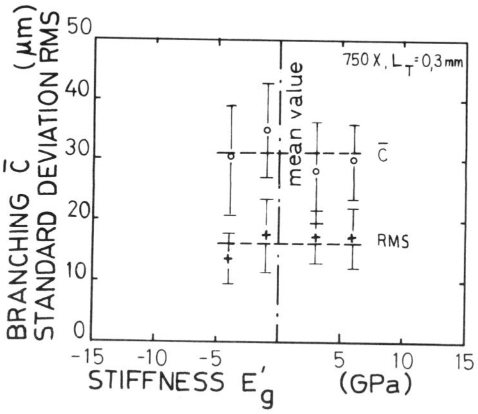

Figure 6 Profilometric standard deviation RMS and mean branching parameter $\bar{C}$, against variation of the initial elastic stiffness E'_g.