INTERPRETATION OF CRACK ARREST FRACTURE TOUGHNESSES MEASURED WITH VARIOUS STEELS

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Crack arrest fracture toughness data measured according to the ASTM test procedure are reported for various steels. All data show a decreasing trend with increasing crack jump distance. It is demonstrated that this behaviour does not result from material scatter alone, but to a significant part is due to dynamic effects influencing the crack arrest process. A simple correction procedure is described that compensates for these effects.

INTRODUCTION

In 1988 ASTM approved a standard test method for determining the plane-strain crack arrest fracture toughness K_{Ia} of ferritic steels: The Final Report on a Round Robin Program conducted to evaluate the proposed ASTM method was published (1) and the test procedure appeared in the Annual Book of ASTM Standards (2). This test procedure was approved only after a long period of research in the field. This previous work is well documented by two ASTM Special Technical Publications (see Hahn and Kanninen (3),(4)).

Introductory remarks to the test procedure give the background of the measuring methodology: The value of the stress intensity factor at the instant of arrest of a fast running crack is considered to represent the ability of a material to arrest a crack. This value, determined by a dynamic method of analysis, is the true crack arrest fracture toughness, denoted K_{IA}. The test method, however, provides a static analysis determination of the stress intensity factor a short time (1 to 2 ms) after arrest. This estimate is denoted K_{Ia}. The static method of analysis is much less complicated than a dynamic analysis. The procedure assumes, that

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K_{Ia} will be a good approximation of K_{IA}, i.e., that the differences between K_{Ia} and K_{IA} will be small, when the macroscopic dynamic effects are relatively small. Restrictions on test conditions, that guarantee that this assumption is fulfilled, are given in the procedure. While it is stated that dynamic analyses may be necessary in certain situations for which the above conditions are not fulfilled, it is believed that the procedure serves at least the following purposes: First, in materials research and development to establish in quantitative terms the ability of materials to arrest running cracks, and secondly in design, to assist in selection of materials for, and determine locations and sizes of, stiffeners and arrestor plates.

This paper (see also (5)) reports on crack arrest fracture toughness estimates K_{Ia} that have been measured following the ASTM standard test method. These data are then critically discussed with respect to their significance in quantifying the ability of a material to arrest a crack and in serving the above cited purposes.

DISCUSSION OF MEASURED CRACK ARREST FRACTURE TOUGHNESSES K_{Ia}

It is customary to discuss crack arrest fracture toughness values K_{Ia} with respect to their dependence on one of two parameters: a parameter that controls the initiation of the crack jump event, i.e. the crack initiation stress intensity factor, K_o, or, a parameter that is controlled by the arrest of the crack jump event, i.e. the arrest crack length a_a or the crack jump distance Δa. It is consistent to consider crack arrest toughness data with respect to a quantity that is also controlled by crack arrest, i.e. a_a or Δa. Such a consideration is in particular advantageous, when the brittle weld technique (see (1)) is used for crack initiation: Due to secondary effects caused by the weld process, e.g. residual stresses, the actual crack initiation stress intensity factor controlling the crack jump event can be very different from the crack initiation stress intensity factor K_o determined in a formal manner from the measured crack opening displacement. This paper, thus, discusses crack arrest fracture toughness data with respect to their dependence on the arrest crack length a_a or on the crack jump distance Δa.

Most crack arrest toughness data have been established within the ASTM Round Robin Program. Twenty one institutions measured four sets of data with two bridge steels, A 514 and A 588 at -30°C, and with the reactor pressure vessel steel A 533 B at +10°C and +25°C. These data are given in Figs. 1-4. The measured crack arrest toughnesses and the corresponding arrest crack lengths are taken from the Final Report of the ASTM Round Robin (1). As is clearly seen, the data show a strongly decreasing trend with increasing arrest crack length. Regression lines are given with the data points to illustrate this trend. In the worst case (steel A 514, -30°C) the measured K_{Ia}-values vary about a factor of 8, typically they vary by factors of about 2 to 4. Not all data points, though, fulfill the validity requirements set forth in the ASTM Test Procedure. The procedure states: First, the crack must propagate at least one plane-stress zone radius past the starter notch, and secondly, the net ligament remaining after arrest must be large enough to provide adequate enclosure of the plastic zone at arrest by an essentially elastic stress field. These requirements result in restrictions on the arrest crack length for data points to be valid, i.e. $0.60 < a_a/W < 0.85$. But even within the validity range given by this condition the general trend of the data is the same: The crack arrest fracture toughness data vary significantly by factors in the range of 1.5 to 2. It is evident, that differences of this size are certainly too large to consider K_{Ia} a good estimate of the true material property K_{IA}, even if the data are looked at from an engineering point of view.

The Final Report of the ASTM Round Robin Program (1) explains this behaviour by material scatter, i.e. by some variability of the material in toughness: It is certainly correct and it can easily be seen, that specimens with high toughness will result in short arrest crack lengths, whereas specimens with low thoughness will exhibit larger arrest crack lenths. Thus, the decreasing trend of the crack arrest fracture toughness with arrest crack length could in principle be explained by material scatter. The following section reports on experiments aimed to check whether this effect is indeed the dominating source for the decreasing trend of K_{Ia} with a_a.

Crack arrest experiments have been performed with specimens made from the high strength steel 38 NiCrMoV 73. This steel has been specially chosen because of its following two properties: First, it is very homogeneous, i.e. the material scatter is very low. Consequently, if material scatter should be the dominating source for the decreasing trend of K_{Ia} with arrest crack length a_a, almost no effect should result for this steel. Secondly, the steel has a considerably higher yield strength (R_e = 660 N/mm², R_m = 862 N/mm²) than the steels tested within the ASTM Round Robin Program (for details see (1)). Consequently, the validity range will be larger than given by the condition $0.60 < a_a/W < 0.85$.

The experiments were performed following the ASTM Procedure, with one difference: The cracks were initiated from differently blunted notches (machined by spark erosion), or from Chevron notches of different angles. In each case, cyclic loading was applied in order to initiate the crack at a predetermined initiation stress intensity factor K_0. The overall specimen dimensions were 250 mm x 243 mm (corresponding to a width W of the specimen measured from the load line of 208.3 mm), the specimen thickness was 20 mm, the initial crack lengths a_0 were in the range of 67 mm to 72 mm, i.e. $a_0/W \approx 0.3$. The measured crack arrest fracture toughness values K_{Ia} are plotted as a function of crack jump distance Δa in Fig. 5. The data scatter closely around a curve which shows a decreasing trend with increasing crack jump distance. This result, thus, is in contradiction to the behaviour that would be expected from the material scatter argument. Furthermore, since no or only very small residual stress effects are expected with the technique used for crack initiation, the measured crack arrest fracture toughness data K_{Ia} are also plotted as a function of K_0 in this case, see Fig. 6. Similar as in the previous plot, the data show a decreasing trend with increasing crack initiation stress intensity factor K_0.

Another series of experiments has been performed with the same steel, 38 NiCrMoV 73, but using specimens other than CCA-(Compact Crack Arrest)-specimens, i.e. RDCB-(Rectangular Double-Cantilever-Beam)- and RDE-(Reduced Dynamic Effects)-specimens. For details of the RDE-specimen see (7) and (8). Although not of primary interest in this context, it shall be mentioned that previous dynamic analyses have shown (8) that dynamic effects influencing the crack arrest process are very large with RDCB-specimens, i.e. larger than with CCA-specimens; but that they are very small with RDE-specimens, i.e. smaller than with CCA-specimens. Here, these two types of specimens are used in addition to the CCA-specimen to investigate possible influences of material scatter on the measured toughness data. Since the material scatter can be expected to be the same regardless of the chosen type of specimen the same variation in K_{Ia}-data should be expected for the three types of specimens.

The data shown in Fig. 7 indicate decreasing curves in all cases, but of different slopes: The largest negative trend is obtained with RDCB-specimens and the shallowest slope is obtained with RDE-specimens. The measured K_{Ia}-data from the largest to the smallest values vary by about a factor of 2.5 for RDCB-specimens, by a factor of almost 2 for CCA-specimens, and they differ by only a factor of about 1.1, i.e. by roughly 10 %, for RDE-specimens. Again, this behaviour cannot be explained satisfactorily by material scatter. This would imply that the same variability of the material would result in different variabilities of the resulting crack arrest fracture toughnesses. Furthermore, the material scatter of this steel definitely will be less than a factor of 2.5.

Similar results as obtained with the steel 38 NiCrMoV 73 have been measured with another very homogenous material showing practically no scatter, i.e. the photoelastic model material Araldite B (6). In addition, numerous results supporting the above findings have been reported by several researchers at meetings of the Working Party on Crack Arrest, Task Group Fracture Dynamics of European Group on Fracture (see (9)).

CONCLUSIONS AND RECOMMENDATIONS

The presented crack arrest fracture toughness data show a strongly decreasing trend with increasing crack jumjp distance. Such a trend is also observed for data measured with a very homogeneous steel showing little material scatter. Furthermore, crack arrest fracture toughness data measured with this steel but using different types of specimens show that the decreasing trend is very different, i.e. the observed differences between the highest and the lowest K_{Ia}-values vary with specimen type.

This behaviour cannot be attributed to material scatter. While material scatter may be the source for part of the decreasing trend of K_{Ia} with arrest crack length a_a for usual structural steels, the dependence obtained with a material showing little scatter, i.e. the steel 38 NiCrMoV 73, is due to fundamental differences between the true crack arrest fracture toughness K_{IA} and the estimate K_{Ia}. As it was pointed out by several authors (see ASTM STPs 627, 711 (3),(4) and also a review article by the author (8)) these differences are caused by dynamic effects influencing the crack arrest process. These effects are shown schematically in Fig. 8: Due to recovered kinetic energy the actual dynamic stress intensity factor at the instant of arrest, K_{IA}, in principle is larger than the statically determined stress intensity factor some time after arrest, K_{Ia}. The dynamic stress intensity fractor approaches the value K_{Ia} via an oscillation with damped amplitude. While the dynamic crack arrest fracture toughness K_{IA} represents a material property being constant and independent on test parameters, K_{Ia} depends on the prior crack propagation history: K_{Ia} is the smaller the higher the crack propagation velocity prior to arrest, i.e. the larger the crack jump distance or the arrest crack length. Only for negligible dynamic effects, i.e. very small crack jump distances, K_{Ia} is a reasonable approximation of K_{IA}.

The presented results on crack arrest fracture toughness data K_{Ia} and the above consideration of the fundamental differences between K_{Ia} and K_{IA} indicate severe shortcomings of the crack arrest toughness estimate K_{Ia}. Advantageous of measuring the true crack arrest fracture toughness K_{IA} by applying dynamic analyses instead of measuring the static estimate K_{Ia} are obvious. As is pointed out in the ASTM Procedure, a dynamic determination of the crack arrest toughness, however, is complicated; possibly too complicated for routine engineering tests. Also RDE-specimens which yield crack arrest fracture toughness data K_{Ia} that suffer very little from influences of dynamic effects although they are based on a static evaluation procedure, are not ideal for routine testing because of their complicated geometry, requiring an extensive time for specimen preparation. The significance of the estimate K_{Ia} in characterizing the ability of materials to arrest propagating cracks, however, can be improved by applying a correction to the measured K_{Ia}-values. The background and the principle of this correction are outlined in the following section.

The author and his colleagues have summarized many crack arrest fracture toughness data measured with CCA-specimens and materials that were very homogeneous and thus exhibited no or little material scatter. For each material these data were normalized by the crack arrest fracture toughness K_{Ia} for crack jump distances tending to zero, i.e. $K_{Ia}(\Delta a \rightarrow 0)$. The data were plotted as a function of the arrest crack length a_a/W. Although measured with different materials, i.e. several high strength steels and the model material Araldite B, the data follow - with some deviations - one single curve. It is assumed that data points in the lower range of the scatter band of this curve are influenced by some unavoidable material scatter. Thus, these points were weighted less when defining a mean curve, shown in Fig. 9. This curve represents a master curve describing the influence of dynamic effects on statically determined crack arrest fracture toughness values measured with CCA-specimens. In this plot the true crack arrest fracture toughness K_{IA} that is independent of the crack arrest length is represented by the dashed line at the ordinate value 1. Thus, a better approximation of the true crack arrest fracture toughness K_{IA} than the ASTM estimate is obtained if K_{Ia} is corrected by a factor that for each crack arrest length accounts for the difference between the master curve and the horizontal K_{IA}-line. The correction factor f_c resulting from this curve has been approximated by a 7th order polynomial. Consequently, a dynamically corrected estimate of the crack arrest fracture toughness is obtained from the statically determined estimate K_{Ia} by the relationship

$$K_{Ia}^{cor} = K_{Ia} \cdot f_c \tag{1}$$

with $$f_c = -21.72 + 319.2(a_a/W) - 1894(a_a/W)^2 + 6150(a_a/W)^3 - 11818(a_a/W)^4 + 13453(a_a/W)^5 - 8406(a_a/W)^6 + 2227(a_a/W)^7 \tag{2}$$

where a = crack length and W = width of the specimen measured from the load line. While the derivation of the correction factor f_c is based on results of many experiments obtained with specimens of a size corresponding to W = 208.3 mm, further experiments are needed to verify this correction factor, e.g. by additional experiments with specimens of different sizes.

The dynamically corrected crack arrest fracture toughness values in general are larger and they show less scatter than the non-corrected ASTM values K_{Ia}. The dynamic correction certainly does not replace a dynamic determination of the true crack arrest fracture toughness, but it yields a quantity that represents a better approximation of the true crack arrest fracture toughness K_{IA} than the non-corrected value K_{Ia}. These corrected K_{Ia}-values, thus, will serve the general purposes claimed by the ASTM-procedure much better than the non-corrected ones.

SUMMARY

Crack arrest fracture toughness values K_{Ia} measured with various steels are discussed. The data show a strongly decreasing trend with increasing arrest crack length. This behaviour cannot be explained by material scatter alone. To a significant part this behaviour is due to fundamental differences between the true crack arrest fracture toughness K_{IA}, i.e. the critical stress intensity

factor at the instant of crack arrest, and the estimate K_{Ia}, determined by a static analysis some time after arrest. These differences result from influences of dynamic effects on the crack arrest process associated with the prior propagation history of the crack. A correction to the crack arrest fracture toughness K_{Ia} is proposed, which compensates in an approximate manner for the influences of these dynamic effects. The corrected K_{Ia}-values represent a better estimate of the true crack arrest fracture toughness K_{IA} and thus serve the purposes of the ASTM test procedure better than the non-corrected values K_{Ia}.

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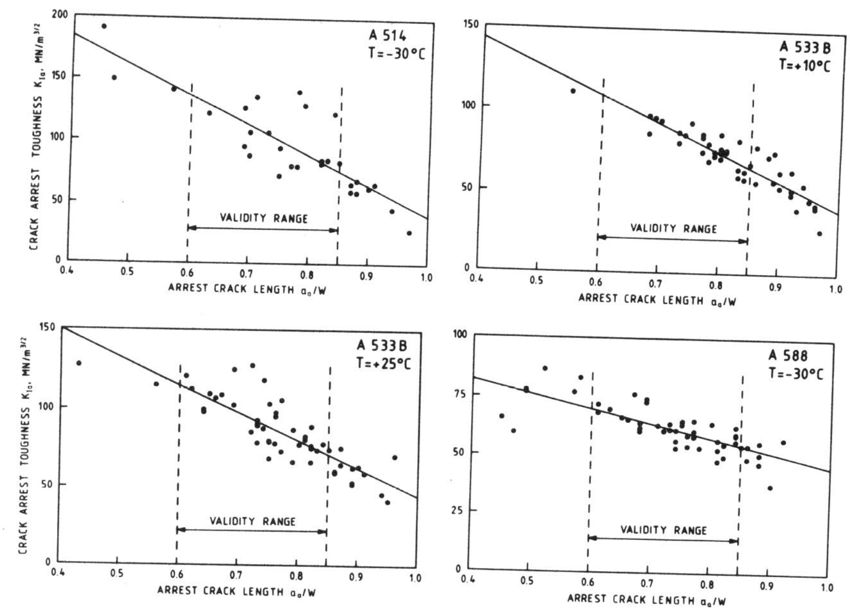
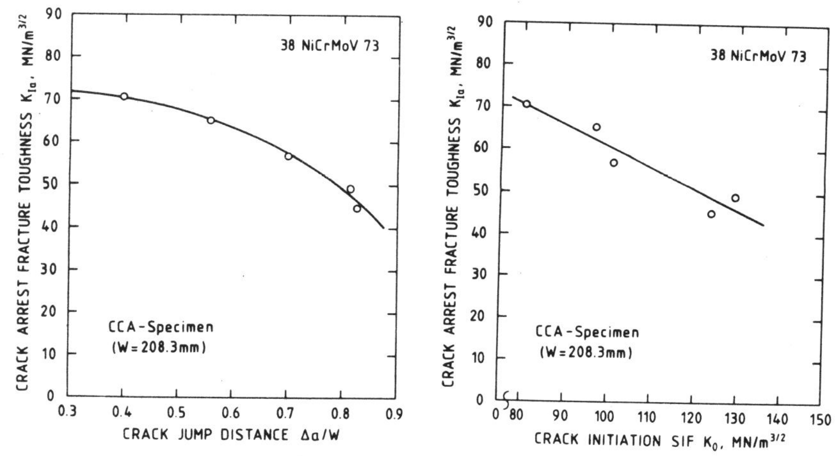


Figs. 1-4 Dependence of crack arrest fracture toughness on arrest crack length. Data from ASTM Round Robin



Figs. 5 and 6 Dependence of crack arrest toughness on crack jump distance (5) and on crack initiation SIF (6), Steel 38 NiCrMoV 73

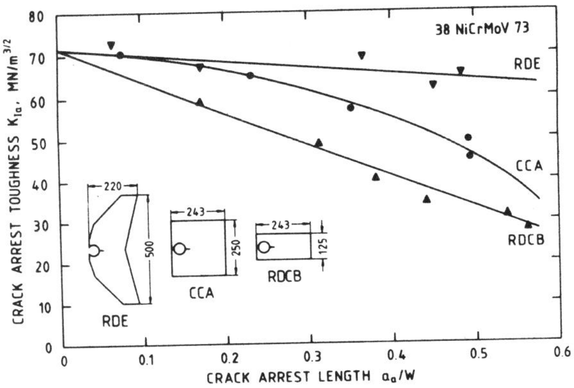


Fig. 7 Dependence of crack arrest fracture toughness on arrest crack length for different test specimens

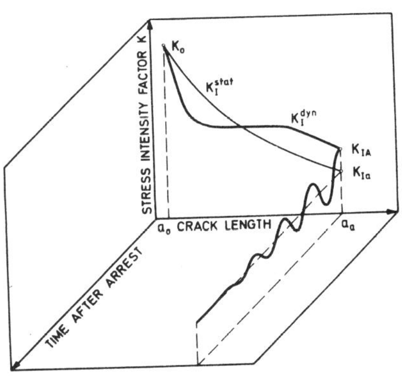


Fig. 8 Influence of dynamic effects (schematically)

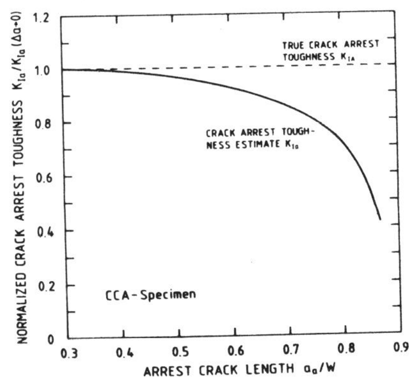


Fig. 9 Dynamic correction function