K_{IC} - A NON-MEASURE
OF PLANE STRAIN FRACTURE TOUGHNESS

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ABSTRACT

The plane-strain fracture toughness, K_{IC}, defined by ASTM E 399, is assumed to represent a size insensitive lower bound value. The interpretation is due to the original work by George Irwin. The materials used for the development of ASTM E 399 were generally aluminum and titanium alloys or maraging steels. The materials had in common that their fracture micro-mechanism was ductile fracture. Even though materials failing by cleavage fracture were not part of the development of the K_{IC} standard, it was soon applied to pressure vessel steels. Also here, it was assumed that valid K_{IC} results are lower bound size insensitive material values showing only little scatter. Based on the present understanding of cleavage fracture, this assumption is known to be incorrect. The misinterpretation is due to the fact that the physical fracture micro-mechanisms were not understood at the time and the developers of the ASTM E 399 testing standard were led astray.

KEYWORDS

Fracture toughness, plane-strain, brittle fracture, ductile fracture.

INTRODUCTION

Structural integrity assessment of structures containing planar flaws (real or postulated) requires the use of fracture mechanics. Fracture mechanics compares in principle two different parameters: the driving force and the material resistance. The driving force is a combination of the flaw size (geometry) and loading conditions, whereas the material resistance describes the materials capability to resist a crack from propagating. Up to date, there exist several different testing standards (and non-standardized procedures) by which it is possible to determine some parameter describing the materials fracture resistance (ASTM E 399, ASTM E 1820, BS 7448, ESIS P2 etc.). Unfortunately, this has lead to a myriad of different parameter definitions and their proper use in fracture assessment may be unclear.

Historically, fracture mechanics evolved from a continuum mechanics understanding of fracture. It was assumed that there existed a single fracture toughness value controlling the materials fracture. If the driving force were less than this fracture toughness, the crack would not propagate and if it exceeded the fracture toughness the crack would propagate. Thus, crack initiation and growth were assumed to occur at a constant driving force value. The only thing assumed to affect this critical value was the constraint of the specimen (or structure). Since at that point of time, there were no quantitative means

to assess the effect of constraint the fracture mechanics, the fracture toughness had to be determined with a specimen showing as high a constraint as possible. This lead to the use of, deeply cracked, bend specimens for the fracture toughness determination.

Historically, the micro-mechanisms of fracture were not considered. It was assumed that the continuum mechanics description of fracture toughness would be valid, regardless of fracture micro-mechanism. This assumption has later been proven to be wrong. Different fracture micro-mechanisms exhibit different physical features that affect the properness of a specific fracture toughness parameter to describe that fracture micro-mechanism.

The common interpretation of the plane-strain fracture toughness K_{IC}, defined by ASTM E 399, is a specimen size insensitive lower bound fracture toughness corresponding to plane-strain stress state. The interpretation is due to the original work by George Irwin where he postulated the expected effect of specimen thickness on fracture toughness (Fig. 1). George Irwin based his conclusions on maximum load toughness behavior of center cracked tension specimens of two aluminium alloys, combined with the specimens macroscopic fracture surface appearance [1]. Even though the experiments did not really correspond to any proper fracture toughness description, nor fracture event, the postulated thickness effect was soon adopted as representing the physical "truth" of fracture behavior. This constituted also the expectations for the development of the ASTM E 399 testing standard.
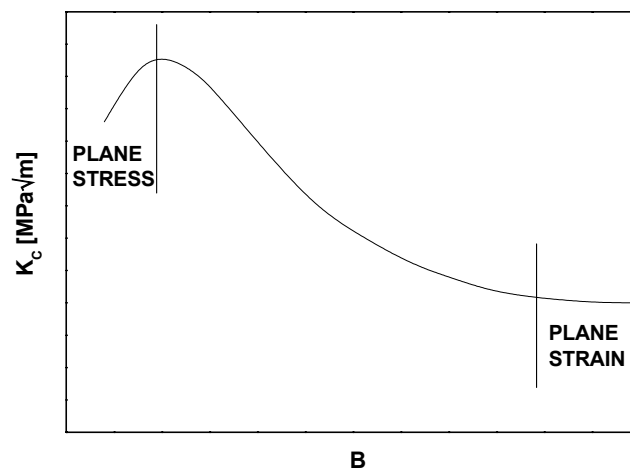

Figure 1: Schematic presentation of the assumption of thickness effect on fracture toughness.

DUCTILE FRACTURE

The materials used for the development of ASTM E 399 were generally aluminum and titanium alloys or maraging steels. The materials had in common that their fracture micro-mechanism was ductile fracture, i.e. the materials showed a rising tearing resistance curve. Unfortunately this was not understood at that time, since the continuum mechanics type of behavior was assumed. This confronted the standard developers with a new problem. Generally, the fracture toughness did not show the expected decreasing trend with increasing specimen size, but the opposite as shown by Fig. 2 [2]. This increasing toughness led to the introduction of the additional demand that $P_{max}/P_Q < 1.1$.

The specimen thickness was still assumed to control the materials fracture toughness as postulated by Irwin. The assumption prevailed, even though the experimental data indicated that it was the specimen ligament size and not thickness that controlled the fracture toughness value (Fig. 3) [2]. The belief in the plane-strain, plane-stress postulate was however so strong that this clear evidence was disregarded.

Also, the plane-strain fracture toughness was assumed to be a lower bound specimen size insensitive material parameter, but the results indicated the reverse, i.e. that K_{IC} increased with specimen size. Since the results were tried to explain solely based on constraint, the real reason for this increase in toughness was never pursued. Based on the present physical understanding of ductile fracture, the increase in fracture toughness is easy to explain.
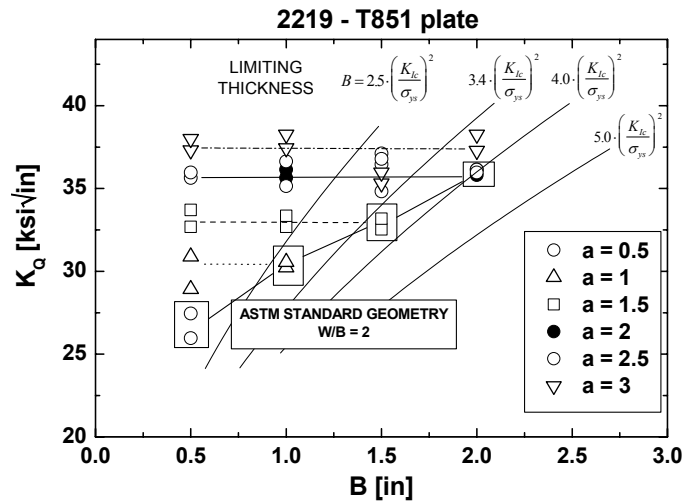
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Figure 2: Old K_Q data used to develop ASTM E399 showing increasing toughness with increasing specimen size [2].
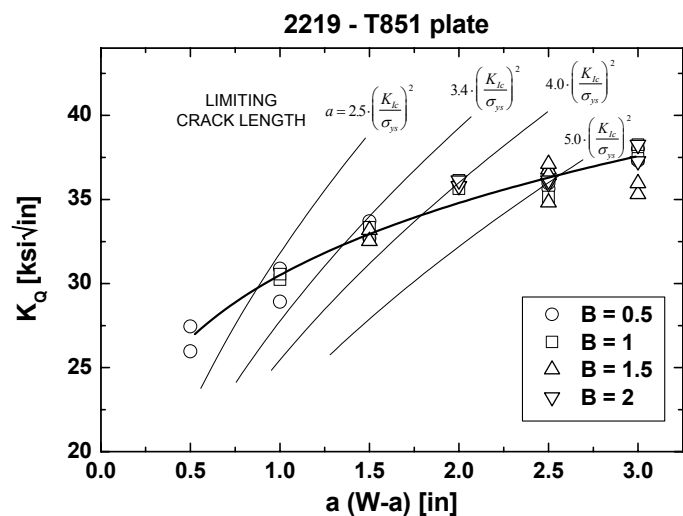
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Figure 3: Same data as in Fig. 2 showing ligament size controlling the increasing toughness [2].

At the time of the development of the K_{IC} standard, there was no reliable means of monitoring crack growth during the test and also, crack growth was assumed to occur at a constant value of K_{IC}. This lead to using the 95 % secant method, for the determination of K_Q. If all the non-linearity in a load-displacement curve of a K_{IC} test specimen is due to crack growth, a 95 % secant correspond to a 2 % crack growth with respect to the ligament. With increasing ligament size, also the absolute amount of crack growth, defined by the 95 % secant, will increase. Knowing, like presently is the case, that materials, in the case of ductile crack growth, exhibit rising tearing resistance curves, makes the increasing toughness with increasing specimen size quite understandable. Fig. 4, is a repetition of Fig. 3, including an estimate of the 2 % crack growth, together with a tearing resistance curve fit. It is clear

that the valid K_{IC} values correspond to considerable amounts of crack growth, the value of which is controlled by the ligament size, not specimen thickness. A modern J_{IC}-test would give for the material in Fig. 4 a K_{JIC} of about 23 ksi√in, i.e. clearly less than the valid K_{IC}.
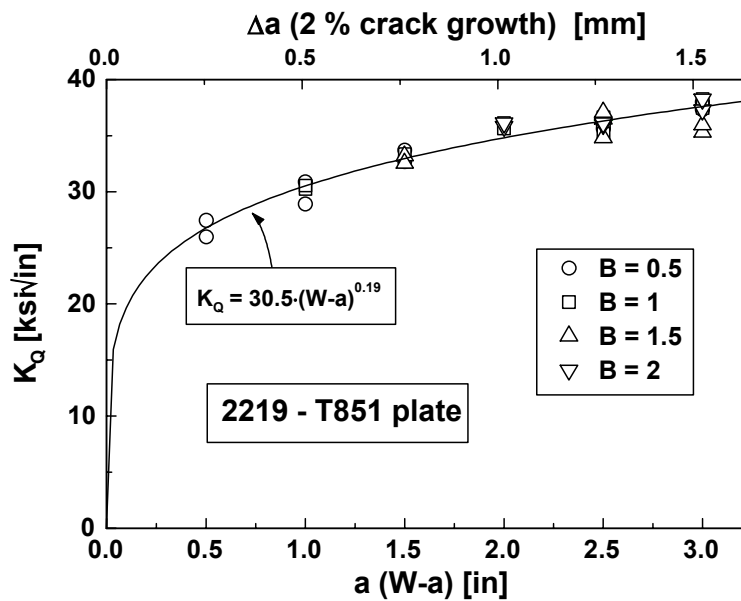

Figure 4: Increasing toughness with increasing ligament size due to increasing tearing resistance curve for ductile tearing.

BRITTLE FRACTURE

Even though materials failing by cleavage fracture were not part of the development of the K_{IC} standard, it soon became applied to testing of nuclear pressure vessel steels. Also here, the original continuum mechanics based philosophy was assumed, i.e. that valid K_{IC} results are lower bound specimen size insensitive material values showing only little scatter. Again, based on the present understanding of the physics of the cleavage fracture micro-mechanism, this philosophical assumption is known to be incorrect.

Based on an interpretation of the physics, the Master Curve method was developed at VTT. Here size effects in brittle fracture toughness are adjusted for, theoretically [3]. Physically, the fracture toughness in temperature space can be divided into three regions, brittle fracture region, transition region and upper shelf. The brittle fracture region is further divided into two separate regions, depending on the way specimen size affects the fracture toughness. In the lower shelf region, size effects are negligible, but at higher toughness values, the brittle fracture toughness will be affected by a statistical size effect. The transition region is defined as the temperature region, where cleavage fracture occurs after some amount of ductile tearing. This region will be specimen size dependent due to the statistical size effect. Finally, the upper shelf is defined as the temperature region where the fracture mechanism is fully ductile. Also the temperature for the onset of upper shelf is specimen size dependent due to the statistical size effect. Besides, statistical size effects, the fracture toughness can be affected by specimen constraint. The basic Master Curve has been standardized by ASTM in ASTM E 1921.

The statistical size effect, due to the weakest link nature of cleavage fracture initiation, is active also for valid K_{IC} results, provided they are above the lower shelf. A good example of this is given by the HSST 02 plate data used originally to develop the ASME K_{IC} reference curve (Fig. 5) [4]. The data, originally known as the "million dollar curve", constituted the first large fracture toughness data set generated for

a single material. Normally, only the valid K_{IC} results are reported, but for clarity, here also the invalid results are included. It is evident that there is a difference between the smaller 1T & 2T specimens and the larger 4T & 6T specimens. This size effect is fully in line with the theoretical statistical size effect as used by the Master Curve methodology [3] (Fig. 6).
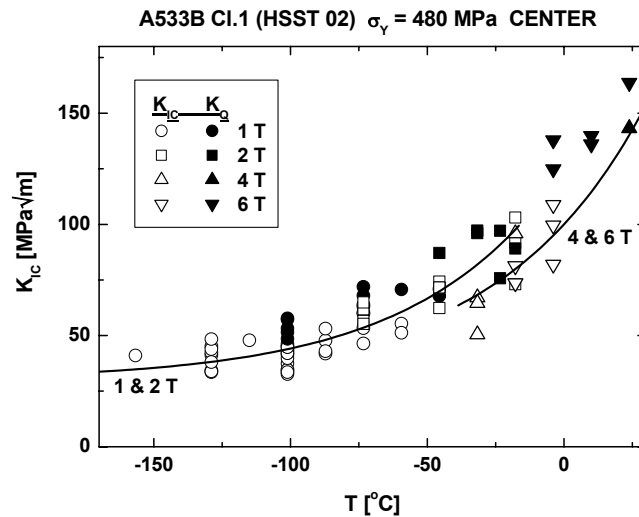

Figure 5: Valid brittle fracture K_{IC} data for the HSST 02 plate indicating decreasing fracture toughness with increasing specimen size.
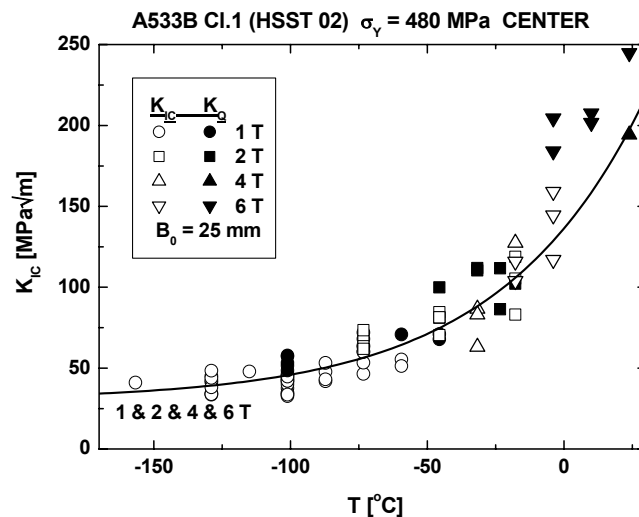

Figure 6: Size effect in valid brittle fracture K_{IC} data for the HSST 02 plate is correctly described with the Master Curve.

Another data set showing the decrease in K_{IC} with increasing specimen size has been presented by MPA (Fig. 7) [5]. Even though the data is limited in number, it clearly indicates decreasing fracture toughness with increasing specimen size, for all valid K_{IC} values. Also in this case, the size effect is in line with the theoretical prediction of the Master Curve. Numerous similar data sets can easily be found in the open literature.
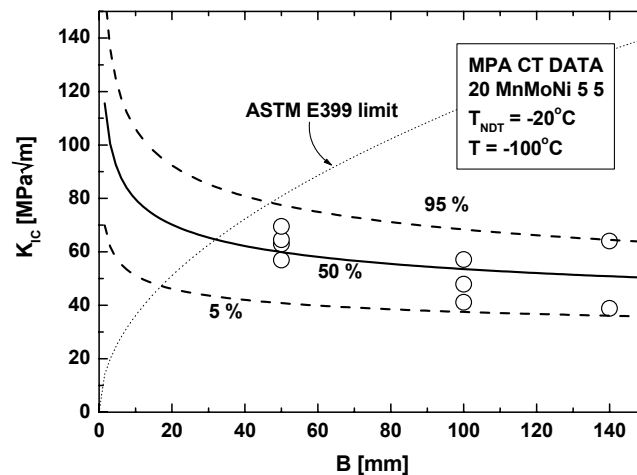
Figure 7: MPA brittle fracture K_{IC} data showing size effect in accordance with the Master Curve [5].

SUMMARY AND CONCLUSIONS

In this work the consistency of the ASTM K_{IC} plane-strain fracture toughness standard (ASTM E399) has been examined based on present knowledge about fracture micromechanisms. Originally the standard was based on continuous mechanics assumptions, which have been found inadequate to describe the real physical fracture process.

It is clear that the classical interpretation of K_{IC} as being a lower bound, specimen size insensitive, fracture toughness value, corresponding to a plane-strain stress state is wrong, both for brittle fracture as well as ductile fracture. The reason for the misinterpretation is due to the fact that the physical fracture micro-mechanisms were not understood at the time and the developers of the ASTM E 399 testing standard were thus led astray. Based on present knowledge, the K_{IC} standard could actually be called a non-measure of plane-strain fracture toughness.

ACKNOWLEDGEMENTS

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