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CHARTING THE FRACTURE TOUGHNESS CHARACTERISTICS OF CASTINGS USING THE DOUBLE TORSION METHOD

C. W. Ten Haagen* and J. T. Berry**

INTRODUCTION

There has been a recent concentration of interest in examining the fracture toughness of cast materials, particularly cast irons. The peculiar features of cast products as well as the product configuration frequently involved present certain difficulties in applying conventional testing methods.

Some of the difficulties are concerned with the relation of test sample size and metallurgical character to casting structure, others to availability of material in section sizes appropriate to conventional fracture toughness testing methods.

At the onset of this investigation it was felt that the double torsion technique might offer several interesting possibilities which could overcome these problems.

TECHNICAL BACKGROUND

Although the application of fracture mechanics to structural design has made extensive progress in the last two decades--particularly in such applications as rocketmotor casing, steam turbine components and large scale weldments, the experimental verification of theoretical predictions has often been limited by the relation of test piece configuration to product geometry. This is often true of castings and forgings.

The casting process lends itself to the economic production of complex shapes. Although there has been a long history of prejudice against cast structural parts on the part of the designers modern casting technology has done a great deal to dispel this. (It is frequently forgotten that many of the critical components in air- and land- based transportation power units are cast). In view of the attractive possibilities of lowering manufacturing costs through more extensive utilization, designers are currently seeking more reliable information upon the fracture toughness related properties of cast materials. This has resulted in the recent appearance of several papers examining the various grades of cast iron from this standpoint.

A further point of interest arises in relation to castings in this respect; whilst for many design purposes in wrought materials, sections may be regarded as having relatively uniform properties, this is not always true

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* Department of Mechanical Engineering, The University of Vermont, Burlington, Vermont, USA.

**School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA.

of castings. Again in wrought materials fracture toughness behaviour for thinner sectioned products cut from a larger sectioned primary shape may be deduced from the properties of the primary shape, although this approach may not be completely valid technically. For cast products, however, no such assumption is possible. Broad variations in material properties from one heat to the next may be caused by changes in pouring temperature, inoculation techniques, heat treatment, and alloy composition. Most importantly, varying casting thickness (and concommitantly the solidification rate) effects internal structural features such as dendrite or nodule size and distribution, segregation of constituent materials, porosity, and subsequently material properties such as yield strength, hardness and fracture toughness. Finally, it will be understood that if the form of the cast product is such that it is not possible to obtain a specimen of the specified thickness, then a valid fracture toughness test cannot be made by *any* recommended method.

Assuming that a valid ASTM test *has* been performed on material obtained from a cast product, the comments above concerning the effects of the solidification rate pose another problem: the fracture toughness value obtained from such a specimen may be misleading in that it may be an accord of a range of fracture toughness properties across the test section of the material. Fracture toughness is theoretically a point property, but its measurement is not, due to the geometrical requirements of achieving plane strain conditions at the crack tip. Currently, the A.S.T.M. test procedure calls for a specimen the thickness of which is 16 times the plane strain radius of plasticity [1] or

$$B = 16\ r = 16\left[1/2\pi\left(\frac{K_{IC}}{\sigma_y}\right)^2\right] \qquad (1)$$

Commonly, this thickness is equal to or greater than the cast product in question. The subject of this work is a test which can measure fracture toughness on a far more localized basis, and, which in addition can "survey" variations in fracture properties along the specimen caused by such factors as the solidification rate.

HISTORY OF THE DOUBLE TORSION TEST

The basic configuration of the Double Torsion test used in this work is shown in Figure 1, its theoretical basis has been outlined elsewhere. This test was first developed by Outwater and Gerry at the University of Vermont in 1966 to measure fracture energy of brittle materials such as glass, epoxy resins, and rock [2, 3, 4]. Modification of the Double Torsion specimen for testing metals was proposed by Berry, and successfully applied to cast and wrought aluminum by Murphy and Kumblé [5, 6, 7]. Up to this point in time, the most notable feature of the test was its ability to measure repeated fracture toughness values independently of the crack displacement--which is not possible with conventional A.S.T.M. test specimens. Principal cast iron types were tested by Ten Haagen [8], and resulted in the observation that consistent fracture toughness values could be obtained with double torsion specimens when the fracture surface thickness (t_c) was reduced to 92% less than the A.S.T.M. specimen thickness (B). Other original work with the Double Torsion test has included measurement of stress corrosion crack velocities in AISI type 4340 steel plate, by Beachem, Kies, and Brown [9], at NRL, and most recently application of test to zinc and aluminum base die cast alloys in Australia [10].

EXPERIMENTAL RESULTS

The novel ability of the Double Torsion test to "survey" variations in fracture toughness values along a specimen length is particularly noteworthy. The techniques employed, together with the processing history and compositional details of the alloys concerned in the present paper have been discussed at length elsewhere [7, 11, 12]. The data in Figure 2 shows typical results from each of three types of materials tested with the Double Torsion test, and illustrates how a point-to-point fracture toughness survey might be made. For simplicity of measurement all values shown are non-fatigue pre-cracked fracture toughness values. It has been shown elsewhere that for a given material these values may be reduced by an experimental constant of proportionality to obtain equivalent fatigue pre-cracked fracture toughness values. The specimens were typically 8 inches long, but fracture toughness values obtained near the plate ends are controlled by "end effects" [7, 8] and have been eliminated from the figures. The fracture toughness values have been spaced in relation to the approximate location of the determination (generally equally spaced).

The distribution of fracture toughness values shown in Figure 2 are for a wrought (2124-T851) aluminum, cast (A357-T6) aluminum, and ferritic ductile cast iron Double Torsion specimens. The wrought aluminum alloy samples were taken from material in the form of 1 3/4 inch (45mm) thick plate. The cast aluminum alloy samples were cut from a variety of locations in a large toroidal shaped casting. The wall section at the locations concerned being approximately 1 3/4 to 2 inches (45 - 50mm). The ductile iron samples were individually cast approximately to size. Table 1 and 2 contain respectively fracture toughness parameter distribution and rate data. Both distribution and range information suggest that for cast products, test blank location does indeed have important effects through the local variation in soundness and structure, one would normally expect from one location to another. For example in the aluminum alloy casting location near the chill showed a secondary dendrite arm spacing of 0.018mm as opposed to 0.024mm nearer the riser. This chill region was also of sounder type of structure which would be associated with more predictable properties. This would appear to be borne out by the range data for the A357-T6 aluminum alloy (Table 2).

The data for the ductile iron (Figure 2) is likewise consistent with this thought in this instance (individually cast test bars) the upward trend of fracture toughness values from the gate end (left hand side of figure) typifies the behaviour seen with this alloy cast in this configuration. Once again one would associate the higher values of fracture toughness with the more rapidly as well as more sequentially frozen material located further from the gate end of the casting.

While the above does not constitute a specially rigorous analysis the potential for future investigations is apparent.

CLOSING COMMENTS

The type of analysis suggested above was made possible by a succession of experimental data and observations made over the past ten years, which have shown the Double Torsion test to be an extremely powerful testing technique. Specifically, some of its characteristics are as follows:

1) The Double Torsion test is applicable to a full spectrum of material types including glass, epoxy resins, rock, aluminum alloys, cast iron and alloy steel.
2) The minimum fracture surface thickness of the Double Torsion specimen (t_c) has been found experimentally to be equal to the plane strain radius of plasticity (r), which represents a 92% saving in this dimension when compared with a valid A.S.T.M. specimen.
3) The thickness saving above may be fully realized by mechanical lamination of an identical slab of the testing material to the top of the test specimen.
4) Only the critical load must be measured, the crack length is immaterial to the determination of fracture toughness with the Double Torsion test.
5) Finally as demonstrated in the present paper, fracture toughness values may be obtained in a continuous fashion along the specimen length and in a far more localized area than any recommended or valid fracture toughness technique.

While the Double Torsion test has been very promising experimentally, information upon the stress state obtaining in the region of the crack front is still required. Consequently a theoretical model must be made to provide a clear understanding of the complex stress fields involved. A finite element method based analysis will be the subject of future work by the authors and their colleagues.

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Table 1 Distribution of Fracture Toughness Values Along Double Torsion Specimens*

Variation Along Aluminum Casting of Type A357-T6. (19 Measurements)

K_Q (MPa·m$^{1/2}$)
38.2
38.5
39.2
39.5
39.3
41.2
42.1
42.4
42.6
42.9
43.3
43.7
43.3
43.3
42.4
42.4
41.5
40.1
39.5

Range 38.2 - 43.7
Average 41.3
t_c = 6.4mm

Variation Along Ferritic Ductile Iron Casting. (11 Measurements)

K_Q (MPa·m$^{1/2}$)
65.2
63.9
66.3
67.5
71.0
71.0
73.3
74.4
72.1
74.4
72.1

Range 74.4 - 63.9
Average 70.1
t_c = 5.2mm

Variation Along Wrought Aluminum 2124-T851 Plate. (10 Measurements)

K_Q (MPa·m$^{1/2}$)
37.3
37.0
37.3
37.4
37.5
36.9
36.1
36.4
37.0

Range 36.1 - 37.4
Average 33.7
t_c = 42.mm

*Values shown are non-fatigue precrack fracture toughness values.

Table 2 Average Values and Ranges of Fracture Toughness Data for Wrought and Cast Aluminum Alloys*

Specimen No.	K_Q	Range R		Note$^{\phi}$
1	41.1	4.4	ID	Between Feeder & Chill
2	37.1	1.9		
3	36.5	2.3	ID	Near Feeder
4	41.2	5.5	OD	
5	39.0	1.1	ID	Near Chill
6†	41.9	0.7	OD	

$\bar{R}$ = 3.1 excludes #6

*Values shown are non-fatigue precrack fracture toughness values

$^{\phi}$Chills and feeders located on casting OD

†Values represent first half of specimen only

Specimen No.	K_Q	Range	Note
1	43.1	1.8	
2	39.9	1.9	
3	39.4	6.6	atypical
4	37.0	1.3	
5	38.7	2.7	
6	37.1	2.6	
7	40.1	3.2	
8	37.1	2.5	
9†	34.9	0.8	see below

$\bar{R}$ = 2.9 excludes #9
$\bar{R}'$= 2.3 excludes #3 and #9

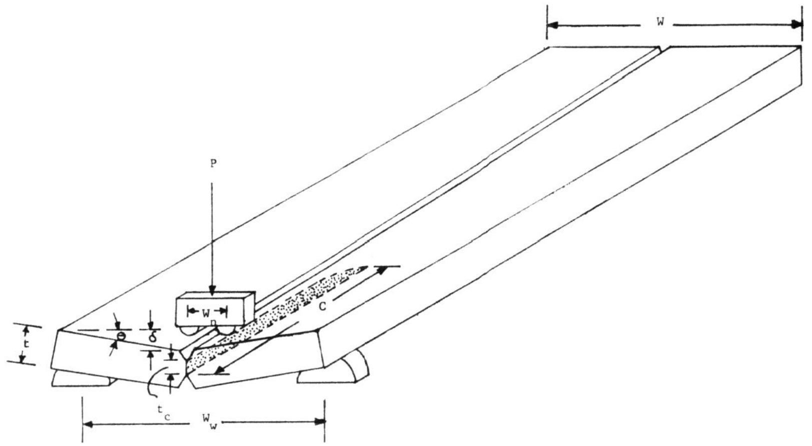

Figure 1 Appearance of Double Torsion Specimen Under Loading Conditions

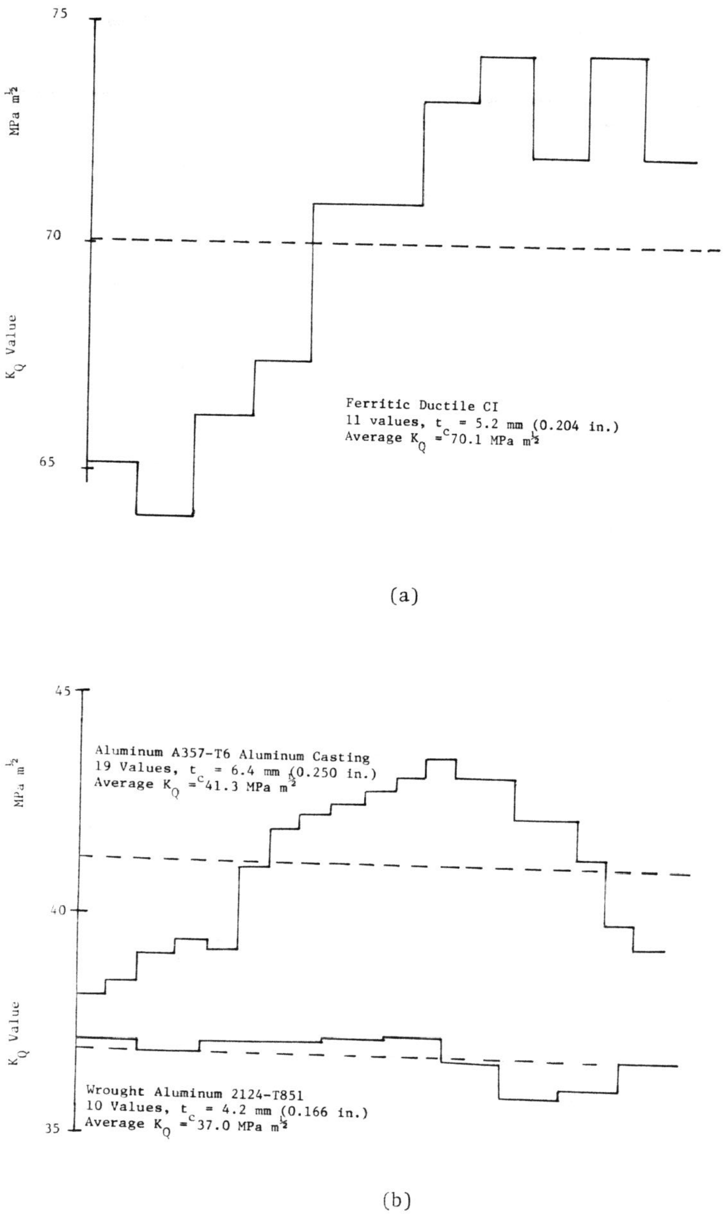

Figure 2 (a) Distribution of Fracture Toughness Values Along Double Torsion Specimen (Ferritic Ductile Iron)

(b) Distribution of Fracture Toughness Values Along Double Torsion Specimens (Wrought and Cast Aluminum Alloys)