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THE FRACTURE TOUGHNESS OF SOME METAL MATRIX COMPOSITES - COMPARISON OF TECHNIQUES

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ABSTRACT

The ability to measure plane strain fracture toughness on small specimens, such as biomaterials and developmental alloys, and on materials that do not lend themselves to fatigue pre-cracking is becoming increasingly important, especially with the profusion of “advanced” materials now being developed. The short rod and short bar chevron notched specimens address this. This paper looks at the correlation between valid K_{Ic} data and short rod fracture toughness (both K_{Iv} and K_{Ivm}) for a series of metal matrix composites. It is shown that the relationship between these values form part of a family of curves that exist for monolithic alloys. The relationship appears to be independent of the use of maximum or critical load values in the calculation of short rod fracture toughness.

KEYWORDS

Metal matrix composites, chevron notch fracture toughness, short rod fracture toughness

INTRODUCTION

In 1977 Barker [1] proposed the short-rod specimen for determining plane strain fracture toughness and this has since been extensively studied. Since then Barker made considerable progress in developing the parameters behind chevron notch fracture toughness [2] testing and in 1978 [3,4] proposed a rectangular cross-section specimen (short bar).

During the early 1980's a number of investigators, for example [5, 6, 7] worked on analysing the chevron notch geometry with a good review of the work until 1984 given by Newman[8]. In 1992, the original analysis was revisited [9]. Much of the work was concerned with comparing fracture toughness measurements with plane strain fracture [10].

The first standard for short rod and short bar specimens, despite the title, was introduced into the ASTM standards in 1987: ASTM B771-87, "Short Rod Fracture Toughness of Cemented Carbides". In 1989, ASTM E1304-89, "Plane Strain (Chevron-Notch) Fracture Toughness of Metallic Materials" was introduced. Due to the fact that this method makes use of a steady state slowly moving crack as opposed to the start of crack extension from a fatigue precrack (ASTM E399), K_{Ic} cannot be used and K_{Iv}: is used to denote the plane strain (chevron-notch) fracture toughness

The lack of a need for fatigue pre-cracking allows for simpler testing procedures. This has resulted in a large variety of materials being tested using this technique for a number of materials [11]. For example poly(methylmethacrylate), (PMMA); polystyrene; polysulphone and polycarbonate [12], silicon nitride and [13], commercially available aluminas [14], a number of biomaterials [15, 16], dental amalgams [17]M-50 bearing steel, alumina, silicon carbide, monolithic silicon nitride and in situ toughened silicon nitride [18] and delamination fracture toughness of several unidirectional, continuous reinforced graphite/epoxy and graphite/PEEK polymer matrix composites [19]. The last four here were tested using modified specimen geometries. Bond strength of thermal barrier coatings [20] and interface toughness of dentin-composites [21], even multiyear sea ice [22], have all had their fracture toughness measured using this technique.

EXPERIMENTAL PROCEDURE

Three types of metal matrix composites (MMCs) were investigated.

- Comral 85, nominally 20 vol% spherical ceramic particles
- Duralcan 20, nominally 20 vol% irregular shaped alumina particles
- Duralcan 10, nominally 10 vol% irregular shaped alumina particles

The matrix was a 6061 aluminium alloy for all MMCs.

The compact tension specimen data were supplied by Hardianfard [23]. All specimens were fatigue pre-cracked and tested in accordance with ASTM 399 Plane-Strain Fracture Toughness of Metallic Materials and the measured fracture toughness is referred to as “K_{Ic}”.

The chevron notch specimens were tested in accordance with ASTM E1304-89 Plane-Strain (Chevron-Notch) Fracture Toughness of Metallic Materials and the measured fracture toughness is referred to as “K_{Iv}”.

RESULTS

The data obtained for the MMCs via ASTM E399 (compact tension specimens) and ASTM 1304 (short rod geometry) are given in Table 1. A range of fracture toughness values was obtained through heat treatment of these age hardenable materials. The terms UA, PA and OA refer to under-aged, peak-aged and over-aged tempers respectively.

There is good agreement between the values obtained from pre-cracked CT specimens and chevron-notched short rod specimens with an average difference of 3.7%. The short rod results generally fell below the values obtained from compact tension specimens.

TABLE 1

FRACTURE TOUGHNESS VALUES OBTAINED FROM SHORT ROD (K_{IV}) AND COMPACT TENSION (K_{IC}) GEOMETRIES.

Material	Temper	K_{Iv} MPa√m	K_{Ic} MPa√m
Duralcan 0%*	PA	-	30
Duralcan 10%	UA	25.7±0.3	26.1±0.3
	PA	23.1±0.3	24.2±0.6
	OA	21.3±0.1	22.0±0.7
Duralcan 20%	UA	24.4±0.5	23.6±0.2
	PA	21.8±0.3	22.8±0.2
	OA	19.7±0.2	21.7±0.9
Unreinforced COMRAL-85 alloy	PA	-	27
COMRAL-85	UA	19.6±0.6	19.0±0.4
	PA	19.0±0.6	18.7±0.6
	OA	17.9±0.2	18.4±0.5

* Data from Duralcan Composites Mechanical and Physical Property Data Sheet, 1990.

For sufficiently brittle materials it has been shown that the short rod result, K_{Iv}, is numerically equal to K_{Ic} [6]. There is a possibility that although there is some good agreement between K_{Ic} and K_{Iv}, the chevron-notched specimen can give a non-conservative measure of toughness when rising R-curve behaviour occurred or there is sample heterogeneity. Marschall et al. [24] found that chevron-notched specimens consistently gave results 18% higher than K_{Ic}. They attributed this to the difference in crack extension in the two specimen geometries and not to any metallurgical differences.

The body of statistical comparisons of K_{Iv} and K_{Ic} are for high strength aluminium alloys. As an example, when differences from metallurgical heterogeneity were removed from the results for a series of high strength heat-treatable aluminium alloys good correlation was found between K_{SB} and K_{Ic}. For a variety of alloys and tempers Brown reported [196]:

$$K_{SB} = 1.017(\pm 0.014)\, K_{Ic} \tag{1}$$

for values of K_{Ic} up to 40.7 MPa√m, where K_{SB} is the fracture toughness obtained form the short bar geometry.

Re-arranging Brown's relationship to give

$$K_{Ic} = 0.983(\pm 0.014)\, K_{SB.} \tag{2}$$

Using the same data compilation technique as Brown a good fit with his relationship is achieved and is shown in Figure 1. The slope of the resultant curve for the data in this study results in

$$K_{Ic} = 0.985 K_{Iv}. \tag{3}$$

This compares well with the reported relationship of Brown.

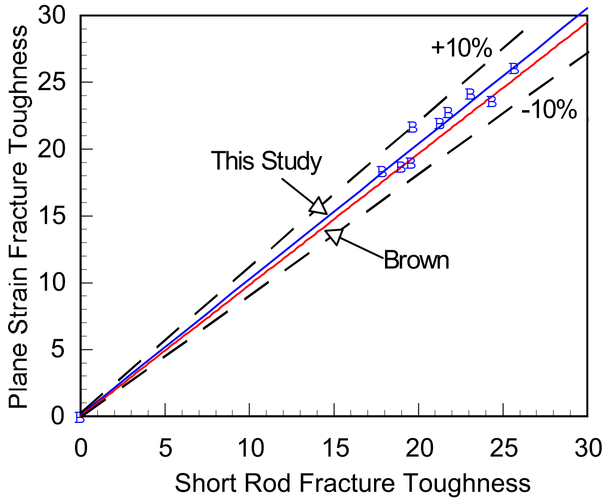

Figure 1. Relationship between K_{Iv} and K_{Ic} for the materials in this study compared to Brown's relationship for a series of aluminium alloys.

Examination of Brown's graphs show that the curve tends to level off at values of fracture toughness above ≈ 35 MPa√m. This may be the reason that the slope obtained for that data is lower than the slope obtained for the MMCs whose maximum value is <30 MPa√m. Despite this reasonable agreement is obtained for the two sets of data.

Other investigators have also tried to develop a relationship to predict K_{Ic} values from short rod or short bar data. These have been based on the calculation of short bar toughness from maximum loads. For example, Bray investigated the use of K_{Ivm} to predict K_{Ic} for a series of aluminium alloys, tempers and orientations in the toughness range of 24-95 MPa√m. Using a linear regression the following relationship was found:

$$K_{Ic} = 0.681(K_{Ivm}) + 9.259 \ (R^2 = 0.929) \qquad (4)$$

Using the short rod fracture toughness data calculated from maximum load the following relationships were obtained for the data in this study:

$$K_{Ic} = 0.75K_{Ivm} + 5.3 \ (R^2 = 0.814) \qquad (5)$$

The Comral-85 short rod specimens had a a 2mm wide particulate rich zone was observed running through the centre, parallel to the extrusion direction, of each specimen and represented some 30% of the crack front width at the critical crack length. This resulted in the temper having little effect on the measured fracture toughness. This has been attributed to the cause of the Comral-85 specimens, in general, having a higher K_{Iv} than K_{Ic} as opposed to the Duralcan materials [11].

If the Comral-85 composites are disregarded due to their inhomogeneity, the Duralcan composites provide a relationship:

$$K_{Ic}= 0.687K_{Iv}+7.83 \ (R^2=0.85) \qquad (6)$$

which compares reasonably well with that obtained by Bray for aluminium alloys. The larger difference for the Bray analogy and the lower correlation coefficient is due to the use of K_{Ivm}, fracture toughness based on maximum load, and indicates the value of the validation checks in K_{Iv} determinations.

None-the-less, if the gradient for each of the relationships found in this and previous studies is plotted against the respective y-intercept a linear relationship of:

$$Y = -26.69G+26.8 \tag{7}$$

(where Y = y-intercept and G= gradient of the K_{Ic} versus K_{Iv} or K_{Ivm} curves) is obtained suggesting that Y and G for these composites form part of a family of curves that exist for monolithic alloys, as opposed to parallel shifts that might have existed and is shown in Figure 3.

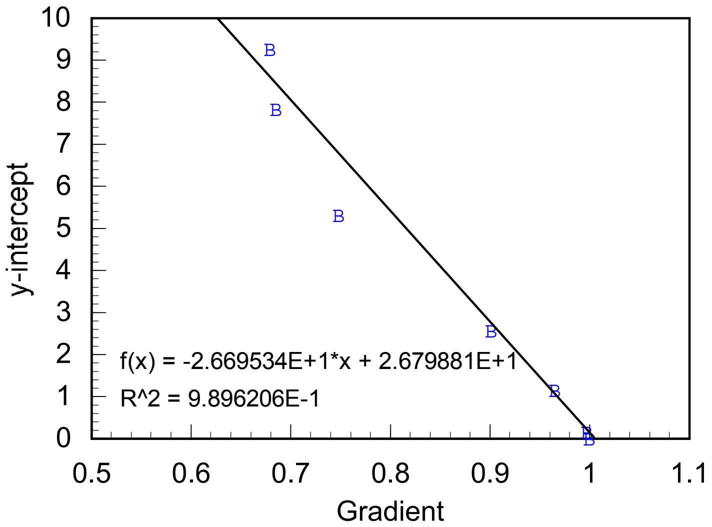

Figure 3. Correlation between gradient and y-intercept for the relations of this study and others.

This relationship appears to be independent of the use of maximum or the critical load to calculate fracture toughness for the chevron-notched specimens. It can be seen that the maximum load values, the first two on the graph, do suffer from the lack of validity checks. For values using K_{Iv} a very good fit is observed.

CONCLUSION

The ability to measure the plane strain fracture toughness of a material in a less expensive manner than generated by ASTM E 399, Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials has been of interest since the 1960's. Most notable of these is the notched tension test, however, there is generally poor correlation with K_{Ic}. Unlike this test the chevron-notched test provides a relative measure of the plane strain fracture toughness.

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