JOURNAL OF MATERIALS SCIENCE 22 (1987) 2927–2932

Torsional fracture of fatigue pre-cracked ceramic rods

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This paper describes the results of an experimental investigation of the room temperature fracture toughness of polycrystalline aluminium oxide (average grain size $\approx 3\,\mu m$) in pure torsion (Mode III). Circumferentially notched cylindrical rods were stressed in uniaxial cyclic compression to introduce a fatigue pre-crack, following a technique proposed earlier; subsequently, the rods were fractured in quasi-static torsion. The critical stress intensity factor for fracture initiation in Mode III is about 2.3 times higher than that measured for Mode I. The mechanisms of quasi-static torsional fracture are contrasted with those observed in the tensile failure of ceramics. The Mode III failure mechanisms in ceramics are also compared with the relatively more familiar cases of torsional fracture in metallic materials. The effects of crack face rubbing and interference between fracture surface asperities on torsional fracture behaviour are highlighted.

1. Introduction

The potential use of advanced structural ceramic materials in a wide variety of engineering components requires a clear understanding of their resistance to fracture under multiaxial loading conditions. Generalized loading situations in practical applications involve combined fracture Modes I (tensile opening), II (pure sliding) and III (torsion/anti-plane strain). The resistance of ceramic materials to fracture in bending/tension/compression (Mode I type failure) has been the subject of extensive research work in the past. To date, very little research has been devoted to the study of fracture in brittle solids in the other modes of loading.

A topic of particular scientific interest and practical importance is the fracture behaviour of ceramics in pure torsion (Mode III). Petrovic and co-workers [1–4] have conducted comprehensive studies of room temperature fracture in ceramic materials under pure tension, pure torsion and tension–torsion loading conditions. They found that the fracture toughness values in Mode III were about 50% greater than those in Mode I for hot-pressed Si_3N_4 [2]. In Petrovic's experiments, the fracture toughness values were measured in tubes and circumferentially notched rods containing no fatigue pre-cracks. The torsional fracture results reported [2, 4] show a (non-coplanar) crack growth deviated by about 45° from the plane of the notch. This would indicate that the observed crack path is a manifestation of a (locally) tensile mode of failure. Chen and Leipold [5] also attempted measurements of Mode III fracture toughness values of soda–lime glass using the tearing of cracked plate samples. They found that the fracture toughness in torsion was about 3.5 times larger than that in tension. However, the validity of their experimental procedure and the possibility of a pure torsional fracture in their tests have been questioned because of the difficulties involved in the tearing of a cracked glass plate [2]. To the author's knowledge, no studies have hitherto been conducted where the failure of ceramic materials in torsion is investigated in specimens containing ("naturally propagated") fatigue pre-cracks (analogous to the procedures widely practised in the fracture toughness testing of metallic materials).

Recently, Suresh and co-workers [6–8] have shown that the application of cyclic compressive stresses to notched plates or rods of brittle solids (e.g. ceramics and ceramic composites) leads to the propagation of stable fatigue cracks. Such flaws emanating from the notch tip propagate at a progressively decreasing rate along the plane of the notch and in a direction macroscopically normal to the compression axis. For the particular case of a microcracking medium, experimental results by Ewart and Suresh [6, 8] and numerical modelling by Brockenbrough and Suresh [9] reveal that this phenomenon is promoted by residual *tensile* stresses which are induced at the notch tip when a population of microcracks within the notch-tip damage zone remains open during unloading from the maximum far-field *compressive* stress. In general, residual tensile stresses are induced in the near-tip region as a result of inelastic deformation in notched plates subject to far-field cyclic compression. The extent of crack growth from the notch-tip can be conveniently controlled by manipulating the compressive stress range and the mean stress as well as the notch geometry. As crack growth under far-field cyclic compression occurs under the influence of a progressively diminishing (local) residual tensile stress field, this

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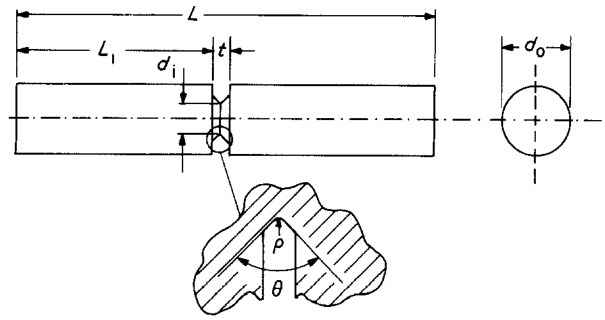

Figure 1 A schematic diagram of the geometry of the specimen.

fracture phenomenon is stable and non-catastrophic even in brittle solids. Pre-cracking in cyclic compression offers a novel capability for introducing sharp fatigue flaws in ceramic materials prior to fracture toughness testing [10].

In this paper, we examine the room temperature fracture characteristics of a polycrystalline aluminium oxide under Mode III loading conditions. Circumferentially notched rods of 99.8% pure alumina are pre-cracked in cyclic compression to produce a uniform fatigue crack using the techniques developed earlier [6–10]. Following this, the specimens are quasi-statically fractured in torsion. We examine the progressive changes in crack morphology from the initiation of fracture to catastrophic failure. The mechanisms of torsional fracture are contrasted with the behaviour observed under tensile loading conditions. The Mode III failure mechanisms in ceramics are also compared with the relatively more familiar cases of torsional fracture in metallic materials.

2. Material and procedure

The material investigated was a 99.8% pure aluminium oxide commercially available as Grade AD 998 from Coors Porcelain Co. (Golden, Colorado). The major impurities in this material consist of SiO_2, MgO, calcium, sodium and iron. The average grain size of this material is about 3 μm and the grain size range is 1 to 14 μm. The room temperature properties of this material are: elastic modulus = 345 GPa, flexure strength = 331 MPa, (unconstrained) compressive strength = 2071 MPa and specific gravity = 3.9. Torsional fracture tests were conducted in the laboratory environment (temperature $\approx$ 23° C and relative humidity $\approx$ 40%) on circumferentially notched specimens (see Fig. 1 for a schematic diagram) machined to the following dimensions: d_o = 19 mm, d_i = 9 mm, L = 115 mm, L_1 = 55 mm, t = 1.8 mm, θ = 60° and ϱ = 0.127 mm. The notch was introduced using a diamond wheel. The specimen was pre-cracked under fully compressive uniaxial cyclic loads at a constant frequency of 15 Hz (sinusoidal waveform) in a closed loop electro-servohydraulic machine. The specimen was placed between two parallel surfaces (where the alignment was checked to avoid bending or buckling) and was loaded under a fully compressive load range of about −50 to −785 MPa for about 50 000 to 150 000 fatigue cycles. The compression loading conditions were designed such that the maximum length of the (concentric) fatigue crack was less than about 80 μm in order to minimize the effect of crack face frictional siding on the measured values of K_{IIIc} (see discussion in a later section). Fig. 2 shows an example of a circumferential fatigue crack originating uniformly

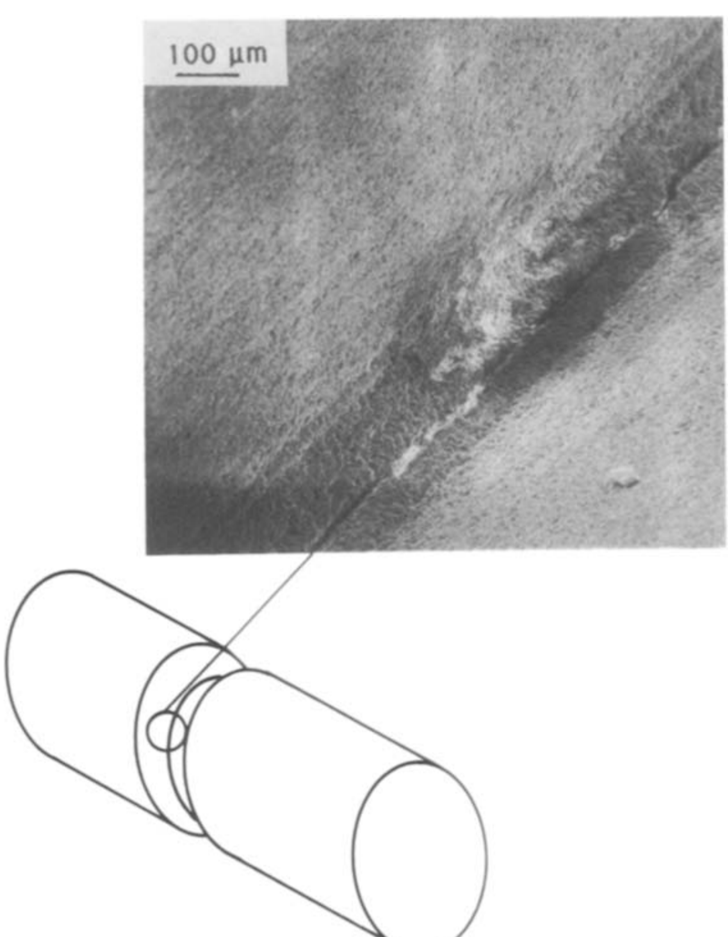

Figure 2 A photograph showing a fatigue crack along the mouth of the circumferential notch.

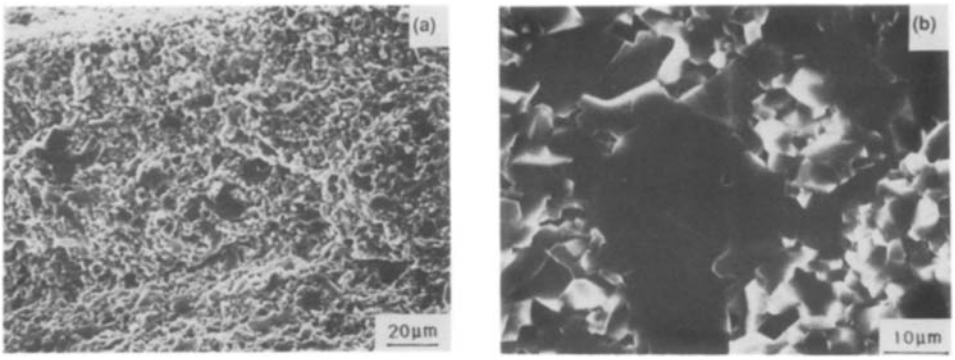

Figure 3 Scanning electron micrographs of the fracture surface resulting from the torsional failure of AD 998 aluminium oxide. See text for details.

along the root of the notch. After the fatigue pre-crack was introduced, the specimen was housed in a tube (whose inner diameter was the same as the diameter of the cylindrical ceramic rod) with longitudinal through-thickness slots and was gripped by tightening the collets around the tube. This specially designed grip was connected to the load train of the servo-hydraulic machine through universal joints. The critical stress intensity factor for fracture initiation in Mode III was calculated from the torque value recorded just prior to the onset of catastrophic failure using the expression

$$K_{\mathrm{III}} = \frac{6T}{\pi d_i^3}\left[\frac{\pi d_i}{2}(1 - \boldsymbol{d})\right]^{1/2} (1 + 0.5\,\boldsymbol{d} + 0.375\,\boldsymbol{d}^2 + 0.3125\,\boldsymbol{d}^3 + 0.273\,\boldsymbol{d}^4 + 0.208\,\boldsymbol{d}^5)$$

where $\boldsymbol{d} = d_i/d_o$ and T is the torque.

3. Results and discussion

The Mode III fracture initiation toughness, K_{IIIc}, of the polycrystalline aluminium oxide was $7.63\,\mathrm{MPa\,m^{1/2}}$. The maximum deviation in K_{IIIc} deduced from several repeat experiments was only $0.2\,\mathrm{MPa\,m^{1/2}}$. Fig. 3 shows scanning electron micrographs of the fracture surface resulting from the torsional failure of circumferentially notched aluminium oxide rod. An important characteristic of the microscopic appearance is the apparently transgranular fracture surface produced by the frictional sliding of the crack faces in torsion (Fig. 3b). Although the principal failure mode is intergranular separation in torsion, the "flattening" of the fracture surfaces due to severe rubbing of the asperities produces transgranular failure regions on the fracture surface. Fig. 4a is a low magnification optical micrograph of the rough fracture surface resulting from the torsional failure of circumferentially notched and fatigue pre-cracked Al_2O_3 rod. This figure reveals a highly tortuous and rough fracture surface due to catastrophic failure under far-field torsion. The mechanism of failure in torsion is significantly different from that observed under pure tension (Mode I) where a circumferentially notched, similarly fatigue pre-cracked ceramic rod exhibits a flat fracture surface (Fig. 4b).

Fig. 5 indicates the state of stress in a solid cylindrical rod loaded in torsion. The maximum tensile stress σ_1 is at 45° to the axis of the shaft. Prior work on circumferentially notched ceramic rods has shown that fracture initiation under far-field torsion occurs at about 45° to the plane of the notch [2]. This implies that the local failure mode is purely tensile in nature and hence the measured critical stress intensity factors for crack initiation under far-field torsion may not represent intrinsic K_{IIIc}. In the present experiments, pronounced mixed-mode failure is observed on a microscopic scale; macroscopically, however, failure occurs uniformly about the plane of the notch. Some salient features of this study are:

(i) The present technique provides a novel capability for measuring the torsional fracture toughness of ceramic specimens containing a fatigue pre-crack (similar to the well established techniques used for the case of ductile metals). The application of cyclic compression stresses to notched ceramic specimens leads to a sharp fatigue flaw. Since the fatigue crack

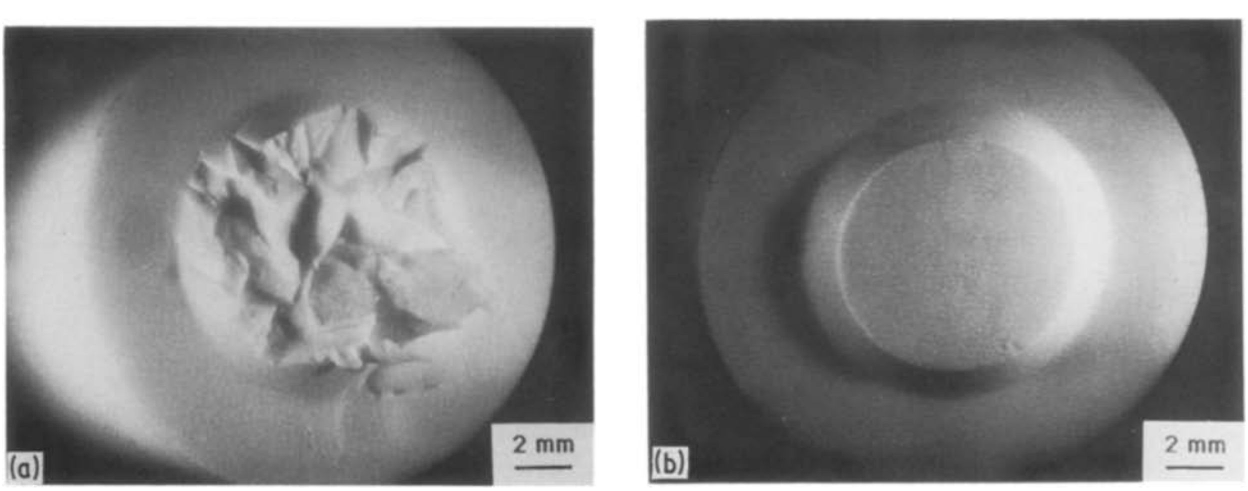

Figure 4 A comparison of (a) the fracture mode under pure torsion with (b) that observed in pure tension.

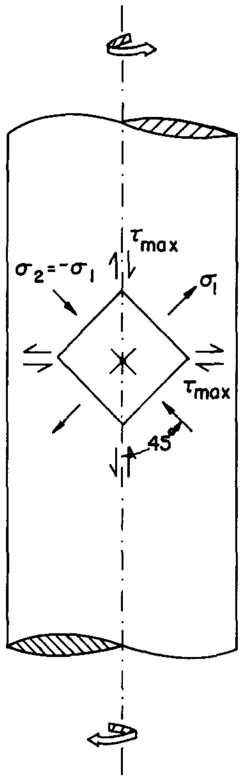

Figure 5 The state of stress in a solid cylindrical rod loaded in torsion.

propagates under the influence of a progressively decreasing "driving force", pre-cracking in cyclic compression provides a stable, non-catastrophic flaw in brittle ceramics even at room temperature.

(ii) Studies of the torsional fracture of metallic materials by Tschegg and co-workers [11, 12] have shown that the measured torsional fracture toughness K_{IIIc} is strongly influenced by the nature of the fracture surfaces and by the total length of the crack (including fatigue pre-crack length and any crack extension during quasi-static torsion). Specificially, the locking of asperities and frictional rubbing between the crack faces plays a decisive role in determining the apparent fracture toughness in torsion; the mechanisms of crack growth during fatigue (pre-cracking) and the consequent roughness of the fracture surfaces can lead to *non-conservative* estimates of K_{IIIc}. Pre-cracking in cyclic compression leads to a sharp fatigue flaw with minimal closure in the wake of the crack-tip during subsequent tension/torsion fracture. Experiments in metals and ceramics have shown that crack growth in cyclic compression promotes a much smoother fracture surface (as compared to cyclic tension) because of the flattening of the asperities under a far-field compressive stress [8, 13].

(iii) A short, concentric fatigue crack (less than about 80 μm in length) was introduced in this work in an attempt to minimize the possible effects of crack face rubbing on the measured values of K_{IIIc}. The pre-cracking procedure, however, enables pre-cracking to different crack length values by suitably controlling the magnitude of the far-field cyclic compressive stress ratio, stress amplitude and the notch geometry.

(iv) As the fatigue crack emanating from the notch-tip advances at a progressively diminishing driving force, the maximum extent of damage left at the tip of a fatigue crack propagated (until self arrest) under far-field cyclic compression is generally not large enough to affect subsequent fracture in tension and/or torsion [9, 13].

Ceramic materials are known to exhibit a predominantly intergranular mode of failure under monotonic tension/bending, monotonic compression or cyclic compression loading conditions at room temperature [8, 14]. Fig. 6 shows an example of the failure mode in AD 998 polycrystalline aluminium oxide fractured at room temperature in pure tension following pre-cracking in cyclic compression. In both compression and quasi-static tension, the fracture mode is predominantly intergranular. On the other hand, torsional fracture of polycrystalline alumina at room temperature involves a significant amount of apparent transgranular separation (Fig. 3c). Severe abrasion between the fracture surfaces (in the wake of the crack tip) leads to a flat fracture surface. Furthermore, the torsional failure behaviour of aluminium oxide at room

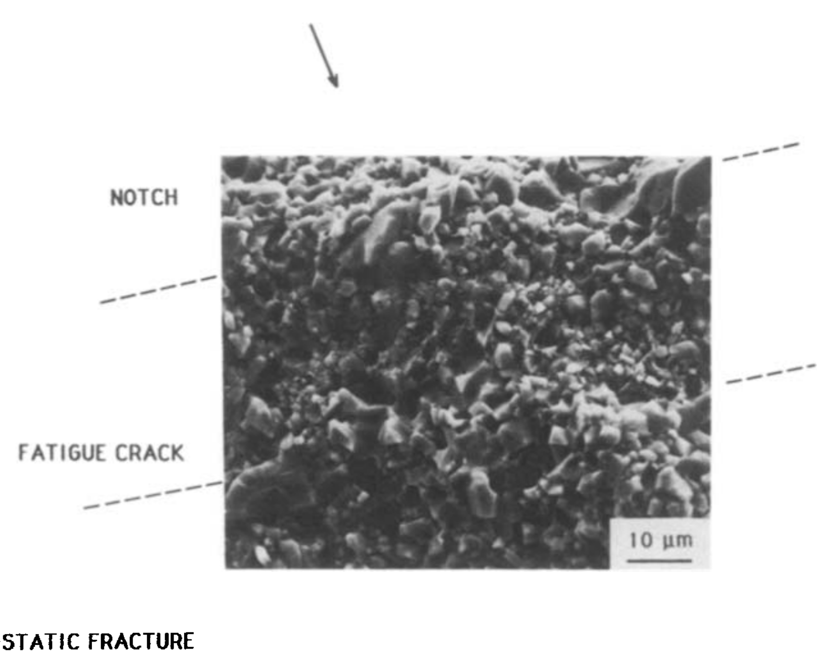

Figure 6 Intergranular separation mode of polycrystalline aluminium oxide fractured at room temperature in uniaxial cyclic compression (region marked "fatigue crack") and quasi-static tension.

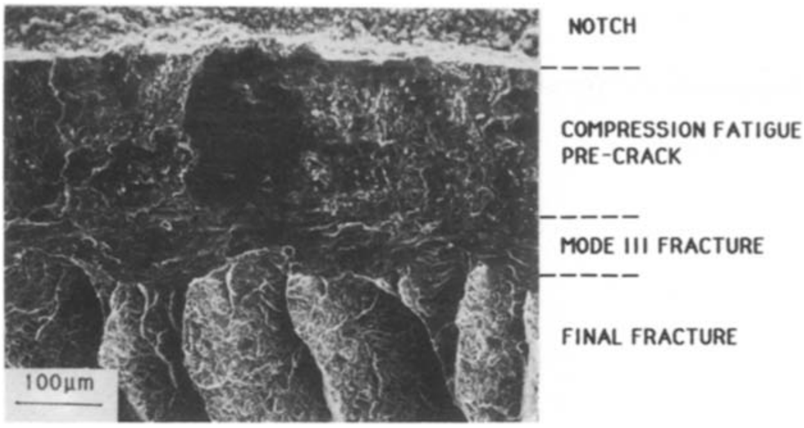

Figure 7 Fracture surface of a circumferentially notched, fatigue pre-cracked cylindrical rod of 4340 steel (tempered at 600° C) fractured in torsion.

temperature is similar to that observed in metallic materials [15–17]. Fig. 7 shows the appearance of the fracture surface of a circumferentially notched and fatigue pre-cracked cylindrical rod of a 4340 steel (tempered at 600° C) which was fractured in pure torsion. Here transgranular separation during the initiation of Mode III fracture is followed by mixed-mode failure leading to a "factory roof" type of surface topography. Locally mixed-mode catastrophic fracture in both metals and ceramics is promoted by the inability of the universal joints to support large torsional displacements; bending moments are introduced in the specimen after a small amount of stable crack growth under quasi-static torsion.

Severe abrasion between the crack faces during torsional fracture imposes a restriction on the determination of a unique toughness value. As the apparent fracture toughness in torsion is strongly influenced by the roughness of the fracture surfaces and the length of the fatigue pre-crack (as well as by crack growth during Mode III fracture), a resistance curve behaviour (R-curve, i.e. increasing far-field driving force with increasing crack length) would be observed. In our experimental procedure, it is not feasible to measure the R-curve because of the inducement of bending moment and mixed-mode failure after a small amount of stable crack growth in pure Mode III. The measurement of an R-curve, for various lengths of the fatigue pre-crack, would provide information on the nature of fracture surface abrasion and its influence on Mode III fracture toughness. In this context, it is interesting to note some recent work on the intrinsic fracture resistance of steels under Mode III conditions. Tschegg [11] measured the fatigue crack growth rates of steels in Mode III with and without superimposed static Mode I loads for a variety of initial crack length values. His results showed that an intrinsic fracture resistance in Mode III can be estimated when the growth rates for various crack lengths and crack opening levels are extrapolated to zero crack length. Recently Tschegg and Suresh [17] obtained an intrinsic Mode III fracture toughness for a 4340 steel using this approach.

In metallic materials, attempts have been made to estimate Mode III fracture toughness, which is independent of crack size and shape, by minimizing fracture surface contact with a superimposed tension [17]. However, such an approach does not appear feasible in ceramics where the crack opening displacement in tension (even for $K_I \rightarrow K_{Ic}$) is typically smaller than the roughness of the fracture surface produced in torsion.

4. Conclusions

A novel procedure has been developed whereby the Mode III fracture initiation toughness values can be measured in circumferentially notched ceramic rods containing concentric fatigue cracks. For the AD 998 polycrystalline aluminium oxide the fracture initiation toughness in Mode III was found to be about 7.63 MPa $m^{1/2}$, which is about 2.5 times greater than the value obtained in pure Mode I. Evidence of transgranular fracture over a very short distance (60 μm) along the plane of the notch is observed during the initial stages of quasi-static torsion. This is followed by catastrophic mixed-mode failure. The various stages of quasi-static torsional fracture in polycrystalline ceramics appear similar to the behaviour observed in metallic materials.

Acknowledgements

This work was supported by a National Science Foundation grant NSF-ENG-8451092. The use of Materials Research Laboratory Central Facilities for Mechanical Testing at Brown University is gratefully acknowledged.

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Received 29 September and accepted 15 December 1986