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Compressive fatigue crack growth behaviour of alumina and glass*

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Cylindrical specimens of polycrystalline alumina and sodium glass with a deep circumferential notch were loaded cyclically under compression, and the fatigue crack-propagation processes in the notch root were studied. The studies showed that debris and a fatigue crack are formed in the notch root of alumina, but not in glass. There, only fragmentation takes place at the crack tip; glass chips are formed which surround the notch. The influence of microstructural inhomogeneities on fatigue crack formation and propagation as well as the consequences for material scientists and engineers are discussed on the basis of a simple model.

1. Introduction

The compressive strength of hard materials like polycrystalline aluminium oxide is usually high, whereas the tensile strength is rather low in comparison with the compressive strength. The main shortcomings of this sort of material are brittleness (and corresponding low toughness) and high notch sensitivity. Notched construction parts made of such materials are consequently designed for loading mainly under compression and only to a small extent under tension. If cyclic loading is expected the fatigue and fatigue crack-growth properties need to be studied.

Research work on crack initiation and propagation under cyclic compressive loading has been performed on a wide variety of materials during recent years, and on a range of different problems. The first fundamental work was published by Suresh and co-workers [1–11]. Single-edge-notched polycrystalline ceramic specimens were used in experimental studies [1] to model and treat initiation and propagation of far-field cyclic fatigue cracks by means of fracture mechanics. The influence of crack closure on fatigue-crack propagation has been demonstrated with single-edge-notched metallic specimens in [2]. Fractographic observations were also performed on metallic specimens and applications for fatigue purposes were discussed for these specimens [3]. Ceramic specimens with a circumferential notch are treated in [4, 5]. Numerical analysis of the stress state along the crack plane was performed for metals [6], for single-phase ceramics, transforming ceramics and ceramic composites [7]. For these studies, the experimental results could be verified. Fatigue cracking during compressive loading was similarly observed in cement-bonded materials such as mortar [8]. Fatigue crack-growth studies have also been performed on polymer materials where crack initiation was found in the notch root [9].

Initiation and propagation of fatigue cracks may be explained as irreversible mechanisms for many materials [11]. For alumina, this has been described in [1, 4, 5, 7, 8]. For glass however, studies on fracturing mechanisms have not previously been published. The question arises if crack initiation and propagation is possible at a sharp notch during cyclic compressive loading in isotropic glass, which does not contain grain boundaries, mobile dislocations and similar defects which may cause irreversible processes at the notch tip. It was the main goal of the present paper to study this question experimentally, as it is interesting not only from a theoretical point of view but also for practical purposes. If a fatigue crack could be formed at the notch root of some glassy construction part by compressive fatigue loading, very small cyclic tension loads would be needed to propagate the crack and to cause unexpected final fracturing of some construction part. Experiments are reported below on alumina and glass, and the results of these tests are compared.

2. Experimental procedure

Cylinders with a circumferential deep notch (as shown in Fig. 1) were chosen for the experiments. Such a specimen shape is useful as it may be precracked in a hydraulic machine without complicated additional equipment such as grips. It is possible to introduce homogeneous deep precracks with this procedure. The front of this kind of crack is not bordered by a free specimen surface so that plane stress conditions cannot arise there; this may be regarded as an ideal basis for a linear elastic fracture mechanics (LEFM) treat-

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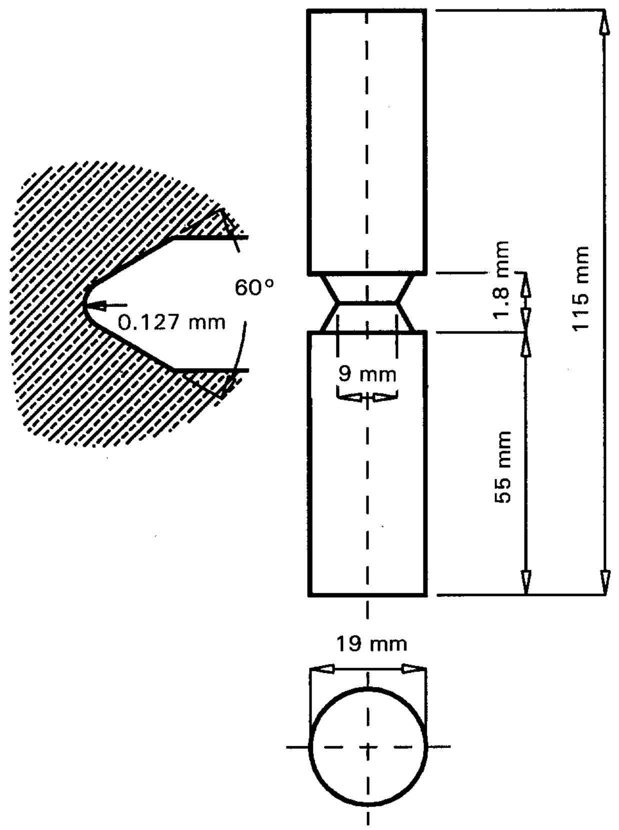

Figure 1 Specimen shape and dimensions for glass and alumina.

ment of cracking. In addition, permanent observation of the precracking procedure is not necessary as the crack-growth rate is decreasing with increasing crack length until the crack stops finally; for more details see [1, 3]. The specimen shape described has been used for studies of mode I, mode III and mixed-mode crack-growth behaviour with much success in the past [3–5, 12].

Polycrystalline alumina (average grain size = 3 μm; maximum grain size = 14 μm; Young's modulus = 345 GPa; compressive strength = 2071 MPa) and soda-lime glass (compressive strength = 830 MPa) have been used as testing materials. The material was shaped as rods with a diameter of 20 mm. The circumferential notch was cut in with a diamond blade.

Fatigue loading was performed with a hydraulic machine (Schenck RSM with a maximum load of 5 t) in load control with a loading frequency of 15 Hz at room temperature and in laboratory air. The load was transmitted via the end planes of the specimens with grips machined from hardened steel, which had parallel polished contact bearing areas. A 0.5-mm-thick piece of cardboard was introduced between grip steel plates and specimen in order to avoid spalling of the specimen edges during compression loading. The amplitude of the sinusoidal compressive load was increased in steps of 10% of the compression strength of the material, as shown in Table I. The number of applied cycles is also listed in Table I. The minimum compressive load was 30 MPa in all tests, to be sure that compression loading prevailed during the fatigue experiment at any time. Fatigue loading was interrupted several times in order to check changes in the notch root area and eventual fatigue crack initiation with a light microscope. After finishing fatigue loading, the specimens were studied in a scanning electron microscope (SEM).

3. Results

In alumina, the amount of debris and the crack length increased with increasing compression load amplitude and increasing number of cycles (see Table I). Fig. 2 shows an SEM photograph of a segment of the notch after finishing the precracking procedure. A fatigue crack with a 2–4 μm wide crack-mouth opening may be recognized. White areas in and around the notch come from debris which are formed during fatigue precracking. The specimens were separated by bending after the fatigue experiments and the fracture

TABLE I Loading conditions

Specimen number	Loading in percentage of compressive strength*	Number of cycles	Comments
Alumina			
1	20	25 000	Few debris visible
	30	25 000	Small short crack and debris
	40	100 000	More debris and pronounced crack
Soda lime glass			
1	20	50 000	No changes in notch root, no debris
	30	50 000	No changes in notch root, no debris
	40	50 000	Slight fragmentation in notch root, no debris
	50	50 000	Fragmentation in notch root, no cracking, no debris
	60	28 000	Catastrophic failure
2	20	50 000	No changes in notch root, no debris
	30	50 000	No changes in notch root, no debris
	40	50 000	Fragmentation in notch root, no debris
	50	45 000	Catastrophic failure
3	20	50 000	No changes in notch root, no debris
	30	50 000	No changes in notch root, no debris
	40	50 000	Fragmentation in notch root, no debris, loading stopped
4	70	600	Specimen fragmented

* Maximum compressive load/ligament area × 100 = pressure strength of material.

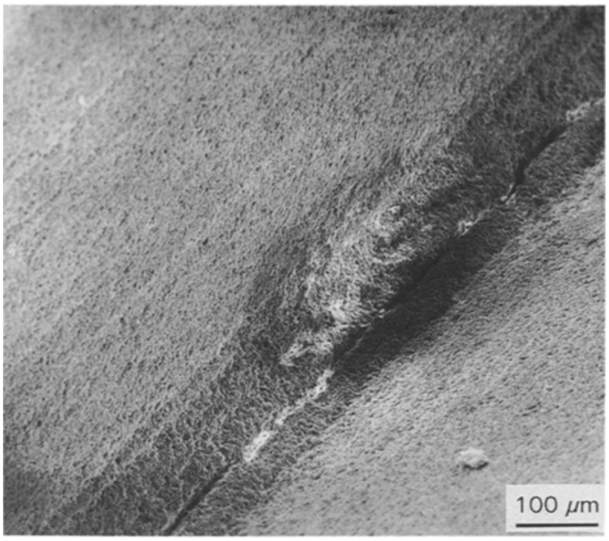

Figure 2 SEM photograph of fatigue crack in the notch of an alumina specimen after loading with a cyclic stress of 20–40% of the compression strength of alumina during approximately 150 000 cycles. The white powder in the notch and within the fatigue crack area are debris which have been produced during fatigue crack initiation and propagation.

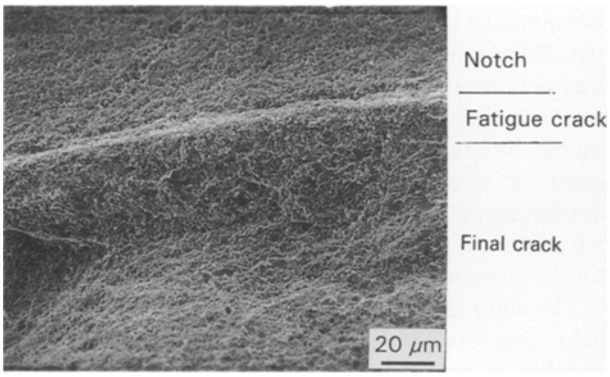

Figure 3 SEM photograph of the fracture surface of a fatigue crack in an alumina specimen which has started in the notch root and has propagated into the inner part of the specimen.

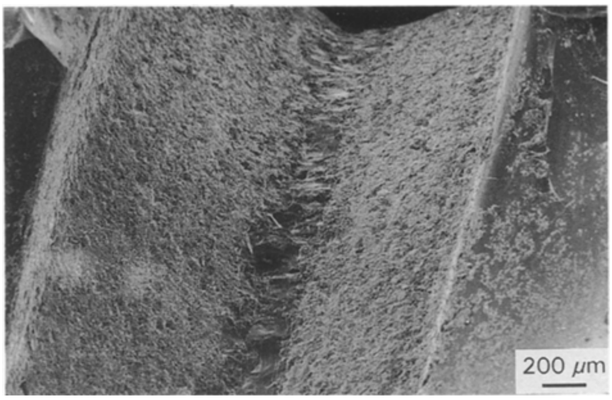

Figure 4 SEM photograph of the notch root of glass specimen No. 3 which was fatigued with a compression load of 40% of the compression strength of glass after approximately 150 000 cycles. Clearly visible is fragmentation within the notch root which causes rounding of the notch tip.

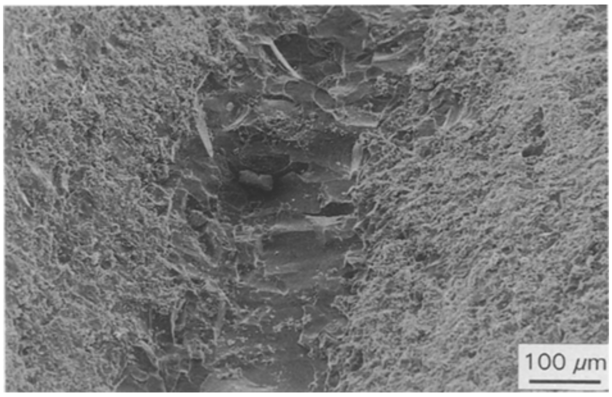

Figure 5 Magnification of Fig. 4. The left and the right side of the figure show the notch flanks. In the centre, fragmentation of the notch root is visible.

surfaces were studied in an SEM. Fig. 3 shows a segment of a ring-shaped fatigue fracture surface which has been formed as an approximately 20 μm wide area (marked in Fig. 3). The difference between fatigue and final fracture is not as distinctly marked as usually in metals.

Glass specimens look quite different. Debris, which are always formed during crack initiation in alumina, could not be observed in any glass specimen (see Table I). Fragmentation takes place at the crack tip, i.e. glass chips are formed at loading amplitudes above approximately 50–60% of the compression strength. Specimens 1 and 2 were fatigued further after these fragments had formed and catastrophic failure took place.

Fatigue loading of specimen No. 3 was interrupted and fragmentation observed in the SEM. Fig. 4 shows part of the notch with pronounced fragmentation in the root. The original surface roughness, as caused by cutting the notch, may be seen at the edges of the notch. The notch root looks similar before fatigue loading. During fatigue loading, glass chips of approximately 10–20 μm diameter are formed, as shown schematically in Fig. 6. The notch root (see Fig. 5) as formed by this process is clearly different from that in alumina (Fig. 2).

Crack initiation or a fatigue crack could not be found along the whole notch root. Specimen No. 3 was broken in a tension machine after SEM observation and the newly formed fracture surface (notch-ligament area) studied in the SEM again. A segment of this fracture surface is seen in Fig. 7 with no evidence of crack initiation. A detail of the fracture surface in Fig. 7 is magnified in Fig. 8. The horizontal area (right side of figure) is the final fracture surface, which is very smooth as usually observed for glass. Perpendicular to this area (left side of figure), part of the fragmented notch may be seen. This fracture surface appears similar to a final fracture, but is characterized by several small fragments. The fine glass 'debris' seen in the right lower and left upper corner of the figure comes from cutting the specimen for observation in the SEM (it can be avoided by cleaning the specimen in an ultrasound bath before introducing it into the SEM).

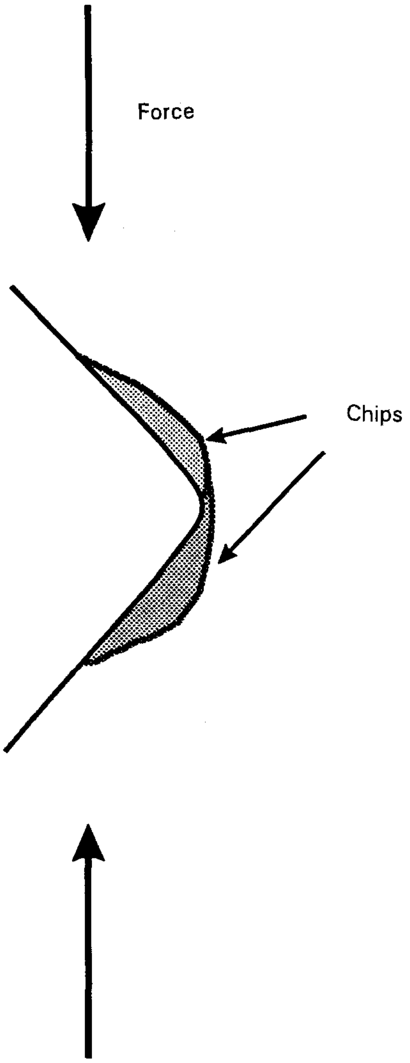

Figure 6 Schematic of the fragmentation taking place at the crack tip, forming glass chips which round the notch root of the glass specimen.

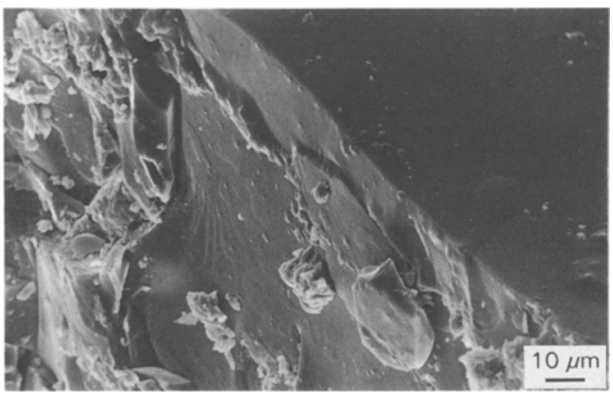

Figure 7 SEM photograph of segment of the same glass specimen as shown in Fig. 4, which was finally fractured after finishing fatigue loading. Nowhere in the whole notch root can sites of crack initiation be recognized.

4. Discussion

The above experiments show clearly that no fatigue crack is formed in glass at a sharp notch by compression loading. This is different from the behaviour of alumina, and the present results on alumina confirm

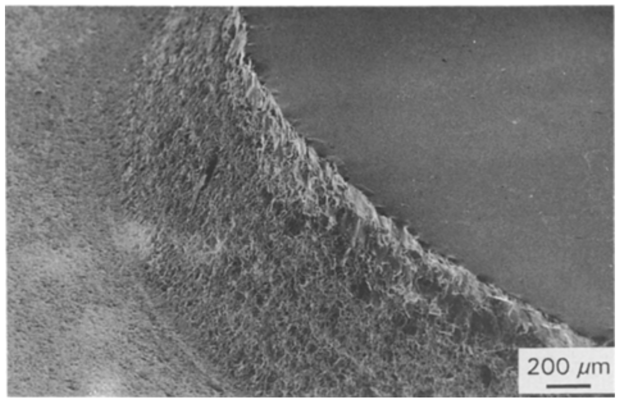

Figure 8 Magnification of details of fracture edge from Fig. 6. The horizontal area (upper right corner) is smooth and glossy and is the final fracture surface. Perpendicular to it (low left corner) the fragmented notch is visible.

previously published results [1, 3, 5, 10]. In glass, fragmentation of small glass chips takes place, and with this the notch becomes less sharp as the notch root radius becomes larger by fragmentation. Fragmentation is probably caused by initiation of small cracks which are oriented parallel to the loading direction (specimen axis). It is well known that high compressive loads generate cracks which are oriented parallel to the load axis. Below, an analysis of the fragmentation procedure with finite element (FE) methods is inserted. In addition, studies are inserted on the initial crack path and the reasons which lead to complete damage of glass specimens at a loading amplitude of 70% of the compression strength, using FE methods. Eventual influences of stress corrosion on the observed fracturing patterns are also studied.

The main reason for mode I fatigue cracking by far-field compression is the formation of a ‘cyclic damage zone’ in ceramic or similar materials and of a plastic zone in metallic materials, so that the (mechanic) residual tensile stresses are reduced or exhausted [10]. These tensile stresses are formed by permanent strains which are formed by irreversible mechanisms and energy consuming (dissipative) processes in the crack-tip zone. The irreversible mechanisms are microcracking (in polycrystalline ceramics and cement-bonded materials, for example), dislocation plasticity (e.g. in metals), stress and strain induced phase transformation (e.g. in transformation strengthened ceramics), frictional sliding along grain boundaries and interfaces (as in polycrystalline ceramics and cement-bonded materials), creep cavitation (in metallic materials) and crazing of shear flow (as in polymers) [1, 9, 11]. The residual stresses generated by these mechanisms are self-equilibrating, which means that an area with tensile stresses is formed adjacent to the notch and an area with compression stresses further away. These residual tensile stresses are reduced during each compressive cycle and are generated again during unloading. The tension stress field is surrounded by an elastic compression stress field, so that crack propagation is stable even in brittle materials.

Microcracking, and possibly frictional sliding along interfaces between the grains, are the mechanisms

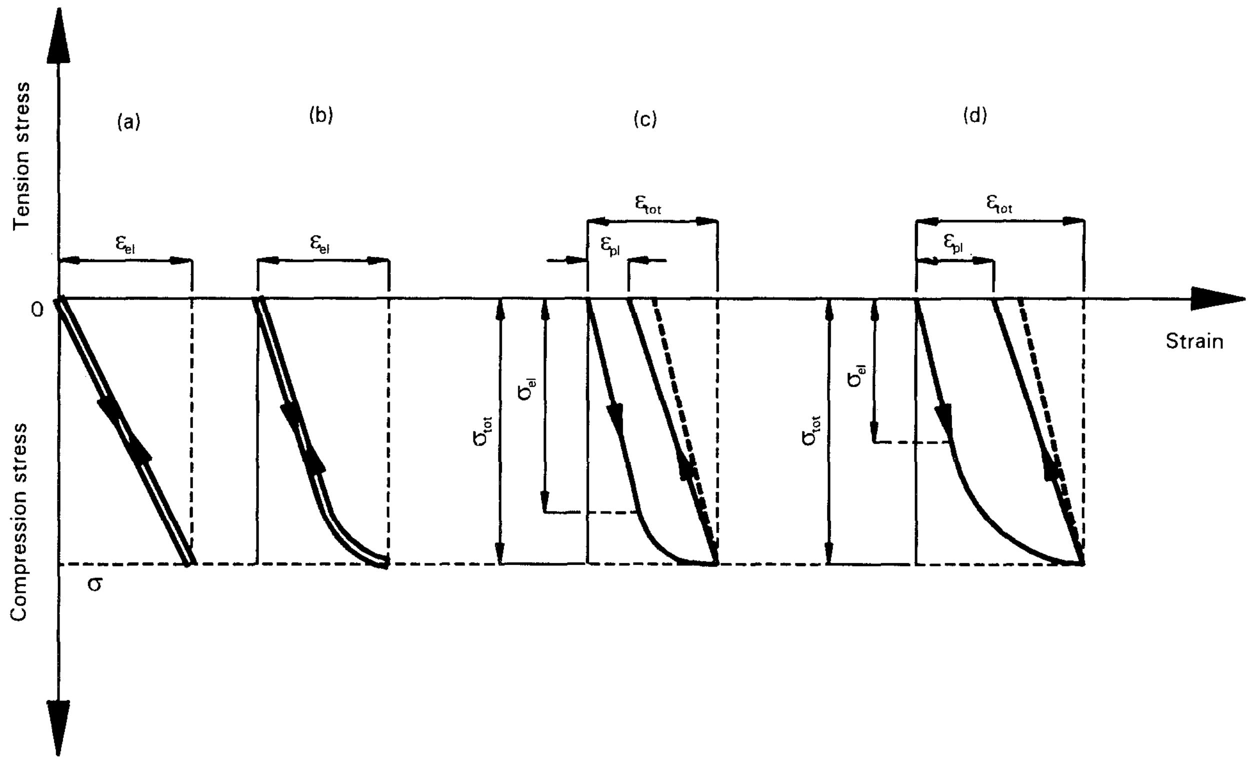

Figure 9 Schematic stress–strain diagram for compression loading and unloading (a) for ideal linear–elastic material; (b) for elastic non-linear–elastic material; (c) for elastic material with minor microcracking; (d) for elastic material with pronounced microcracking.

which generate residual stresses in the notch root. Glass is isotropic, and does not contain structural elements or structural features which are appropriate to generate irreversible strains in the material or are able to dissipate energy. Therefore, crack initiation and propagation do not occur in glass as in alumina and in many other materials.

From this observation it may be concluded that energy-dissipating and irreversible processes, respectively, make crack initiation and propagation in brittle materials possible and promote them. Such processes are also used in brittle materials to raise their fracture toughness. It may be assumed therefore that these mechanisms have two opposing effects: increase of fracture toughness on one hand, and facilitating fatigue crack initiation and propagation on the other. This fact is of great interest for material scientists and design engineers and should be further discussed.

The results of this work are similar to [1, 8, 11] in a simplified model, as follows. The stress–strain behaviour under compressive loading is shown in Fig. 9 for materials with different mechanical behaviour. For an ideally elastic material (Fig. 9a) the loading and unloading curves are identical. The strain ε_{tot} is equal to the elastic strain ε_{el}. Irreversible or energy-dissipating processes do not occur during repeated loading or unloading, and therefore a crack cannot be formed at the notch root. If the material under discussion is characterized by non-linear elastic behaviour (Fig. 9b), the same is true as for Fig. 9a. Glass behaves as shown in Fig. 9a or b. If the material studied shows a small amount of 'plastic' behaviour after elastic deformation (which is caused by one or several of the above mentioned mechanisms) a loading and unloading diagram results, as shown schematically in Fig. 9c. The dashed curve for unloading is true for ideally elastic behaviour which does not really occur in practice. During unloading, processes such as closure of microcracks occur, which reduce the slope of the unloading curve (full curve). Some 'plastic' strain, ε_{pl}, remains present after unloading and this gives rise to a tension stress and crack formation in the notch root. This behaviour is typical for alumina.

If material with higher fracture toughness is loaded, 'plastic' straining is more pronounced and begins to be effective after only small linear elastic deformation has taken place. During unloading a large amount of 'plastic' deformation, and consequently a high tension stress, remains present in the notch root facilitating the formation of a fatigue crack (Fig. 9d).

In order to avoid fatigue cracks, loading must be low enough to avoid 'plastic' behaviour of the material. As may be seen from Fig. 9c and d, material with low 'plastic' deformation capability may be loaded with a higher fatigue load without generating a fatigue crack in the notch root, in comparison with materials with high 'plastic' deformation properties and thus a higher fracture toughness. This result has to be considered by material scientists and engineers.

5. Conclusions

Crack initiation and propagation were studied on cylindrical alumina and glass specimens with a deep circumferential notch under compressive cyclic loading. From microscopical observations, the following conclusions are drawn. In alumina, crack initiation and propagation are promoted by well-known mechanisms. Compression fatigue loading leads to irreversible and energy dissipating processes, and thus permanent strains in the process zone at the notch root, which cause generation of fatigue cracks. In glass, such processes are not possible owing to the different microstructure of this material, and fatigue-crack initiation therefore cannot be observed in the notch root even at high cyclic compressive loads. Instead of this, fragmentation with small glass chips occurs in the notch root, which causes rounding of the notch tip so that the notch becomes less sharp.

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