

Fatigue behaviour of fine-grained alumina hip-joint heads under normal walking conditions

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Abstract. In prosthetic applications, the reliability of implant materials over a period of thirty years is absolutely essential. Calculation of the lifetimes of alumina ceramic heads is generally made on the basis of experimental fatigue and slow crack growth tests using finite element analysis. This investigation is aimed at understanding the fatigue behaviour of fine-grained alumina heads of hip joints. The service conditions of cyclic stress experienced by hip joints during walking are used in evaluating the fatigue behaviour of alumina femoral heads. These femoral heads have successfully withstood 10^7 cycles at a maximum walking stress of 17.2 kN, which is equivalent to a body weight of 400 kg. The femoral heads did not exhibit any sub-critical crack growth at the maximum walking load of 10 kN, indicating the quasi-infinite performance life in patients up to a body weight of 250 kg. The details of proof testing designed for evaluating the performance of femoral heads over 40 years are also presented.

Keywords. Hip joint; femoral heads; alumina; fatigue; crack growth.

1. Introduction

Alumina-based fine-grained ceramics are currently preferred to their metallic counterparts for fabrication of different types of orthopaedic implants needed for replacement of worn-out bone-joints. This material is exceptionally inert in the physiological environment and offers excellent bio-compatibility (Boutin 1981). Further, alumina in highly pure form offers very high compressive strength and picks up very good surface finish resulting in exceptionally low coefficient of friction (Dorre *et al* 1975) and wear rates (Mckellop 1981). It has been found that the amount of aluminium lost inside the body from the implant surface is negligible in pure and dense alumina and only a very thin ($< 50\text{Å}$ thickness, Williams 1981) hydrated layer of $\text{Al}(\text{OH})_3$ is formed on the surface in contact with body fluids. Alumina has a hydrophilic surface, which results in a coating on its surface with a layer of water molecules. This absorbed layer of water and other materials provide the ceramic with excellent protection from further reaction with the body and appreciably reduces wear at the ceramic–bone interface.

However, like all other materials, alumina too fails under fatigue conditions at loads much below the critical failure strength and as the material is brittle in nature, failure occurs without any prior indication resulting in catastrophe. Pearson (1950) claimed that the deterioration

in strength of Al_2O_3 under static fatigue depends on the combined effect of moisture and stress. Krohn & Hassleman (1972) demonstrated a thermally activated process in the cyclic fatigue of alumina, while Ko (1986, 1989) correlated the static bending and fatigue strength of sintered alumina by an $S-N$ curve generated by experimental values. Guiu, Vaughan and others (Vaughan & Guiu 1987; Guiu & Vaughan 1986; Vaughan *et al* 1987; Reese & Guiu 1990) introduced a novel technique to study the tribological effect on the fatigue properties of bio-grade Al_2O_3 under normal/fluid environment. Attempting to simulate fatigue conditions, they performed repeated indentations with varying sub-critical loads on the same position having a pre-indentation with a higher load till chipping occurred. Thus an $S-N$ curve was constructed which differed from similar curves obtained by cyclic loading. Earlier workers (Sarkar & Glinn 1969; Huffine & Berger 1977; Maity *et al* 1994) have demonstrated the susceptibility of Al_2O_3 ceramics to impact fatigue and explain that the stresses induced by shock are more damaging.

For prosthetic application of alumina, reliability is an essential prerequisite and therefore mechanical behaviour of the material for a period of 20–30 years is of utmost importance. Such behaviour cannot be deduced easily from standard mechanical tests because they have to be carried out for extremely long durations to generate meaningful results. An alternative method is to make a calculation of the life-time of ceramic heads on the basis of experimental fatigue and slow crack growth tests using finite element analysis.

In the present study, as the first approach, the fatigue behaviour of fine-grained alumina, which is used to make the heads of the hip joint, was investigated under different repetitive loading conditions. Further, in this case unlike the sinusoidal stress as reported by many researchers (Dorre & Dawihl 1980; Heimke *et al* 1980; Tateishi & Yunoki 1987), cyclic stress as experienced by a normal hip-joint during walking was directly applied on femoral heads made of alumina and the results are discussed. In this case, heads of small diameter are chosen to generate very low polyethylene wear rate (Clarke *et al* 1993).

2. Materials and methods

A high-pure variety of alumina powder (chemical analysis is given in table 1) was wet-mixed with 0.25% MgO, dried and pressed isostatically at a pressure of 150 MPa to prepare blocks. These blocks were subsequently turned into the specified shapes needed for evaluation of different physical and mechanical properties. Test samples were subsequently sintered at

Table 1. Chemical analysis of alumina powder used in the present study.

Constituents	Weight (%)
Al_2O_3	99.5
SiO_2	Trace
Fe_2O_3	0.06
TiO_2	Trace
CaO	Trace
MgO	Trace
K_2O	Nil
Na_2O	0.05
ZrO_2	Nil
LOI	0.03

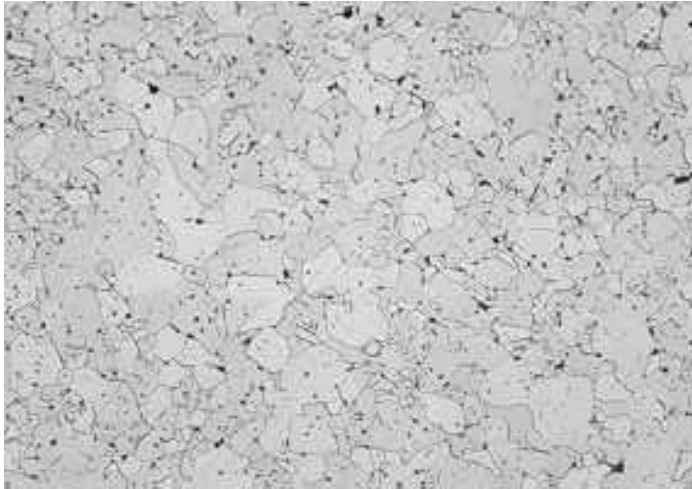


Figure 1. Optical photomicrograph of alumina used for the present investigation.

1550° C for 2 h in an electrically heated furnace and were finally polished with diamond paste to a CLA (centre line average) of 0.1 micron. The average grain size of the sintered material was found to be 1–3 micron (see figure 1).

Transverse rupture strengths (TRS) were measured on a four-point bending fixture with stressing rate of 10 MPa s⁻¹ using an Instron universal testing machine (model no. 1185). Hardness was measured using the Vicker's hardness tester. Elastic modulus of the material was estimated by an ultrasonic velocity measurement using Kraut Kramer USIP 12 tester interfaced with a Philips 3350, 100 MHz oscilloscope. The fracture toughness K_{Ic} was determined from the length of the cracks generated at the corners of the vicker's indentation with different loads from the following relationship:

$$K_{Ic} = 0.016(E/H)^{1/2} P(C)^{-3/2}, \quad (1)$$

where E is the Young's modulus, H the hardness, P the indentation load, and C the crack length. A comparison of the properties of sintered specimens with that of the ISO specified values for similar materials, is presented in table 2.

Table 2. Comparison of the physical and mechanical properties of alumina used in the present study with ISO specifications.

Properties	Materials of CGCRI	ISO specification (IS:5347 – 1984)
Density (gm/cm ³)	3.94	3.90
Bulk density (gm/cm ³)	2.70	–
Micro-hardness (GPa)	23.00	23.00
Compressive strength (MPa)	4500	4000
Flexural strength (MPa)	420	> 400
Young's modulus (GPa)	390	> 380
Wear resistance (mm/h)	< 0.01	< 0.01
Corrosion resistance (mg/m ⁻² day ⁻¹)	0.05	0.1

2.1 Static and cyclic fatigue

Static fatigue behaviour of alumina under constant load was studied on a 4-point bending fixture in an electro-servo hydraulic Instron machine of 20 kN capacity. The corresponding failure time for each sub-critical applied load was recorded for an S - T plot. The specimens were loaded at the rate of 22 N/s up to a predetermined level and during the operation the instrument was kept under load control mode. Cyclic fatigue was studied under a sinusoidal stress waveform where a stress ratio of 0.5 was maintained with a frequency of 5 Hz. The mean value of the cyclic stress was kept identical with the value of the static stress. A computer recorded all the load deflection data along with the number of cycles required for fracture. In some of the samples, cracks of measured lengths were generated deliberately by Vicker's indentation with predetermined loads (100 N, 200 N) to measure the crack velocity under different loading conditions. The crack velocity V was determined from the relationship as follows:

$$V = da/dt = AK_1^n, \quad (2)$$

where a is crack size, A and n are constants (slow crack growth parameters) that mainly depend on the material and the environment. From (2), the time of failure (t_f) under constant/cyclic applied stress (σ_a) can be calculated by the relationship of Ritter (1978)

$$t_f = B \cdot S^{n-2} \sigma_a^{-n}, \quad (3)$$

where $B = (2/AY^2)(n-2)K_{1c}^{n-2}$, S = fracture strength of the material when no sub-critical crack growth occurs. In (3), t_f represents the time required for a flaw to grow from an initial sub-critical size to dimensions critical for catastrophic propagation and B and n are the constants that characterize sub-critical crack growth.

2.2 Fatigue of the femoral heads

Cyclic fatigue of femoral heads was investigated by an Instron Hip-Joint simulator (model no. 8511.20). This is basically a fatigue-testing machine equipped with software which measures the stress on the test piece, equivalent to the actual stress experienced by a natural human hip-joint, in various postures. A schematic diagram of the machine is provided in figure 2.

Further the machine is capable of providing a rocking motion within $\pm 20^\circ$ to the acetabular polyethylene cup to simulate the relative motion that occurs between the femur head and the acetabulum in an actual situation. A typical load curve on the hip joint of a patient of 100 kg body weight during level walking is represented in figure 3. In the present investigation, the ceramic heads were exposed to loads corresponding to the loads experienced by the femur heads of patients with 100, 250 and 400 kg body weight for up to 10^7 walking cycles. The tests were repeated under water-lubricated conditions for which the temperature of the water bath was maintained at 37°C . Finally some of the fatigued heads after being fitted with a stainless steel anvil were subjected to uni-axial slow compression till fracture occurred to estimate crack propagation during the fatigue-testing period.

3. Results and discussions

Figure 4 represents the results of the static and cyclic fatigue of Al_2O_3 . The logarithms of constant stress in case of the static tests or the peak (σ_{\max}) in the cyclic tests is plotted against the logarithm of both time, t and number of cycles to failure, N .

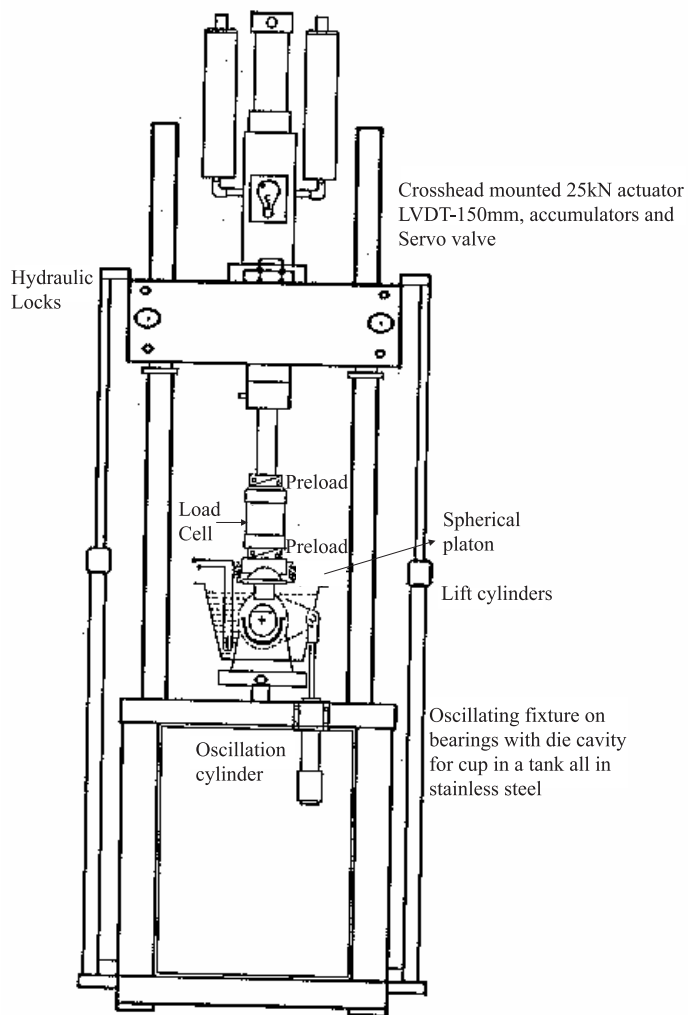
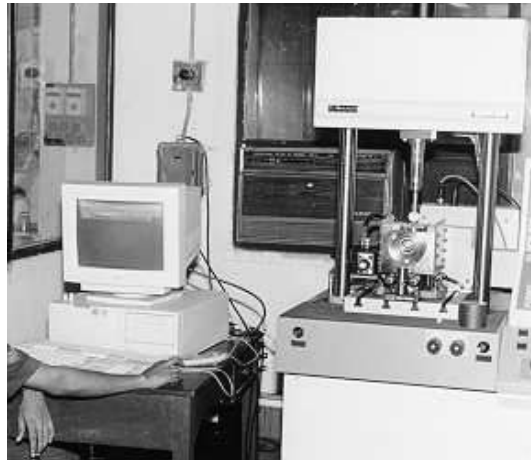


Figure 2. The hip-joint simulator with its schematic diagram.

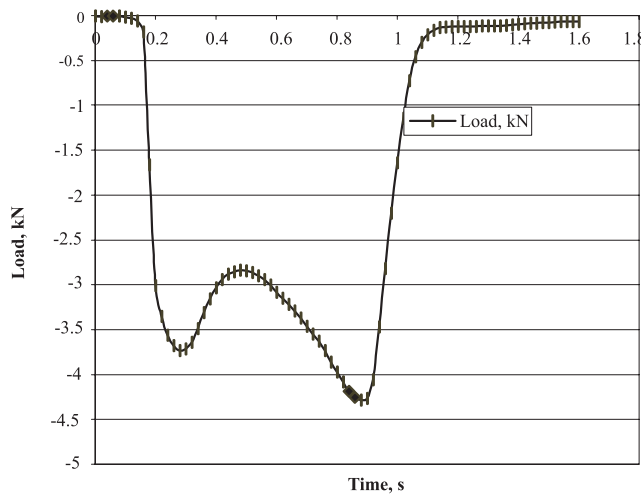


Figure 3. Typical stress pattern experienced by a human hip during walking (the body weight of the person is assumed to be 100 kg).

The experimental data was thus fitted to a relationship:

$$\log \sigma_{\max} = (1/n) \log N + C, \quad (4)$$

or

$$\log \sigma_{\max} = (1/n) \log t + c, \quad (4)$$

where C is a constant and n the fatigue resistance parameter. It was apparent that n for static and cyclic conditions for alumina were 30 and 25 respectively. The results are more or less in agreement with the values reported in the literature (Guiu 1978; Reece *et al* 1989). Fatigue behaviour of ceramic materials is mainly controlled by slow crack growth from pre-existing flaws introduced into the ceramic material either during shaping (bulk flaws) or during machining or finishing operations (surface flaws). The single most common mechanism responsible for fatigue crack growth is stress corrosion at the crack tip. The results of slow crack growth behaviour of alumina samples of different grain sizes under different static and cyclic loadings have been reported by Kishimoto *et al* (1994). They clearly established that fatigue crack growth in alumina is more or less a linear function of applied stress intensity and is significantly influenced by the inherent grain size of the material. Further, they claimed that crack growth is faster under cyclic fatigue. These observations are also evident in the present investigation.

The results of static and cyclic fatigue study on identical samples with indented pre-cracks of specified size have been summarized in figures 5a and b. The results reveal that in both the cases the fatigue resistance parameter or the endurance limit to the breaking stress ratio did not change significantly and the moderate deviations were well within the scatter of the data points. However, in each occasion the threshold stress values to initiate crack propagation were significantly reduced with the increase in crack size.

Figure 6 represents the results of the stress analysis on the ceramic balls as obtained by finite element analysis. The figure shows that the tensile stress on the ball under any loading condition is highest at the point C and it progressively increases with increase in the effective stress on hip-joint i.e. with the body weight of the patient and also with the decrease of contact area. This signifies that the maximum stress on a ceramic head of given dimension decreases as the contact area between the cup and the head increases. For the purpose it is

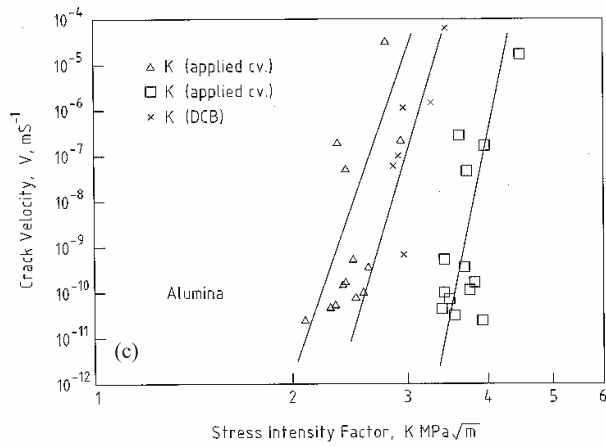
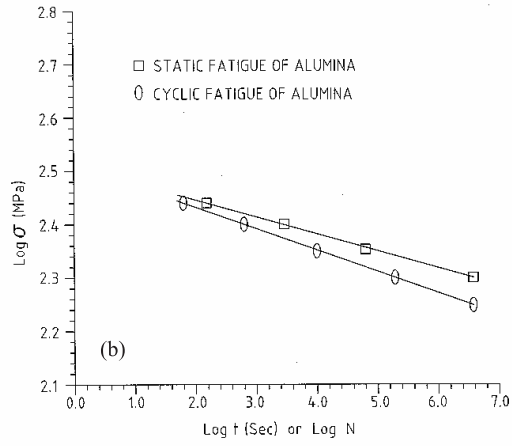
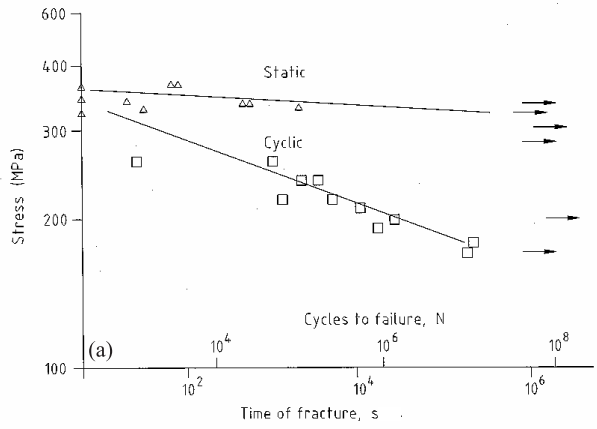


Figure 4. Static and cyclic fatigue data of alumina.

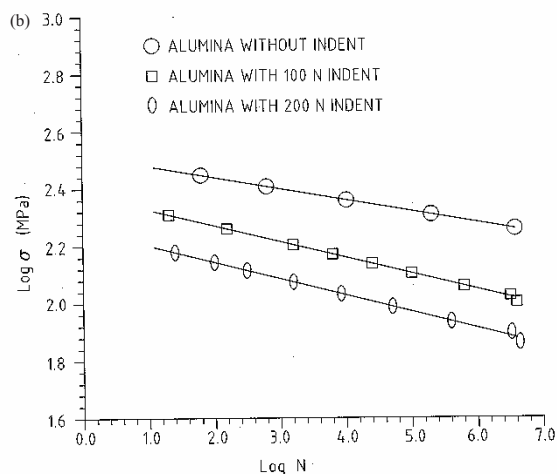
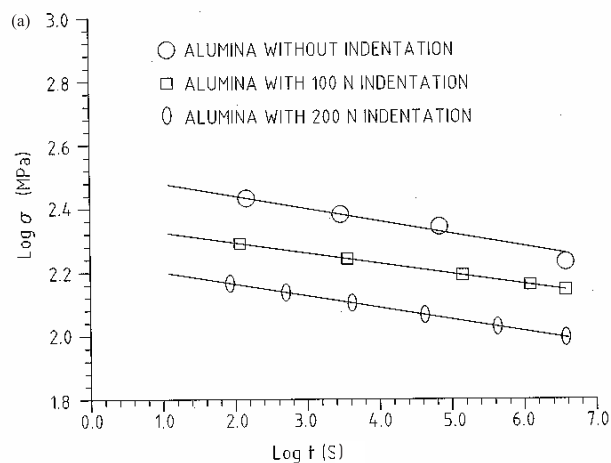


Figure 5. (a) Static and (b) cyclic fatigue behaviour of alumina with and without pre-indented cracks.

better to use a comparatively softer material in the acetabular cup which creeps and wears out with continuous articulation to increase the contact area resulting decrease in the stress concentration within the ceramic head. The figure shows that at 10 KN load (which occurs in a person with about 250 kg body weight) on the hip-joint the point C experiences a stress of 300 MPa when the diameter of the contact area is about 10.7 mm. In case of the present system with alumina cup of 28 mm diameter the contact area was measured to be in the range of 16 mm and therefore the maximum stress experienced by the C point of the ball for a person of 100 kg body weight was much less than 100 MPa while for a person of 400 kg body weight this value is about 250 MPa which is slightly higher than the endurance limit of alumina.

However, all the heads were exposed to 10^7 walking cycles and all of them withstood the test parameters. Even the sphericity of the heads were checked after each test and no appreciable change was noticed. During the tests the ceramic head penetrated into the acetabular cup

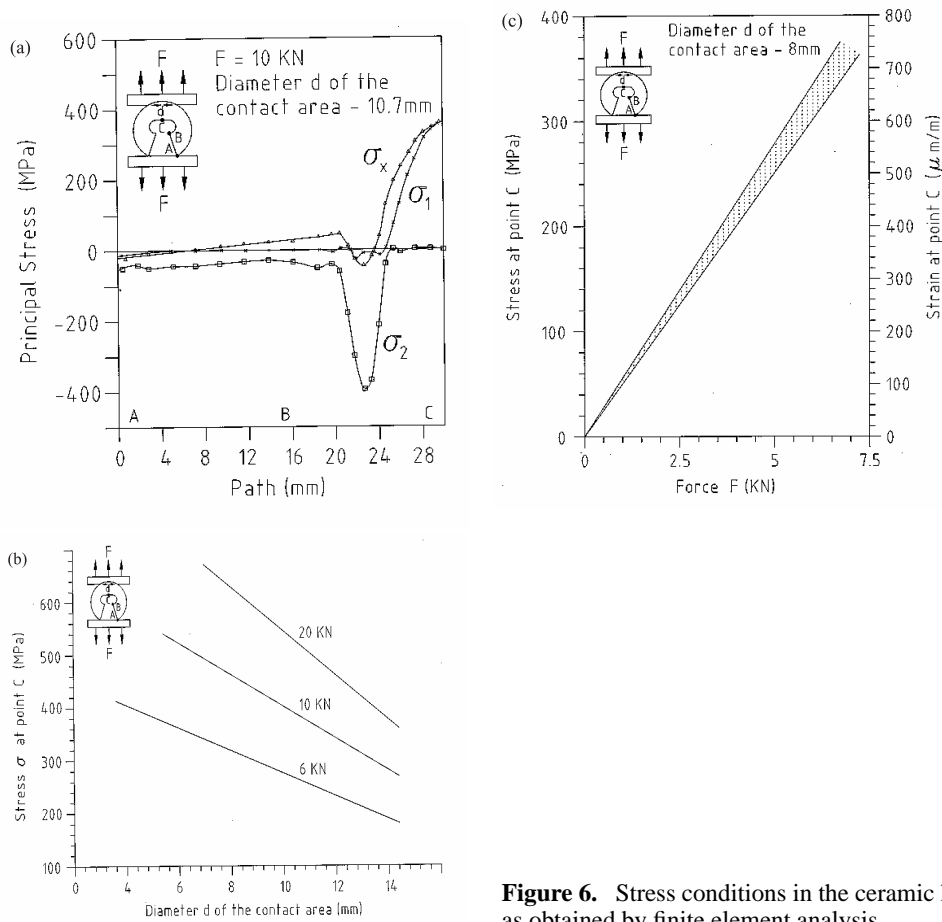


Figure 6. Stress conditions in the ceramic head as obtained by finite element analysis.

and the phenomena is summarized in figure 7. The results reveal that the penetration, which occurred due to exposure to the walking load without rocking motion, gives an account of the creep deformation of the polymer cup while the data with the rocking motion represents the combined effect of creep as well as the wear of the cup due to articulation. It is also evident that even after an equivalent walking cycle of 10^6 , wear of the polymer cup is only about 30 microns and this confirms the superiority of these material combinations for the present application.

None of the fatigued heads when exposed to the uniaxial load failed below 31 kN. The average fracture strength of the fresh ceramic heads were found to be 48 ± 6 kN while the ones exposed to the load equivalent to body weights of 100 kg and 250 kg did not show any degradation in strength values, 49 ± 10 kN and 47 ± 9 kN respectively. The results clearly indicate that fatigue due to walking with a maximum stress of 4.3 kN (100 kg body weight) and 10.0 kN (250 kg body weight) did not induce any slow crack growth in the alumina heads of 28 mm diameter. This confirms that the maximum stress intensity factor generated at any point inside the heads were lower than the threshold value for fatigue crack propagation and therefore the life of these heads under similar conditions is expected to be quasi-infinite. The fracture strength of the heads exposed to maximum walking stress of 17.2 kN (400 kg body

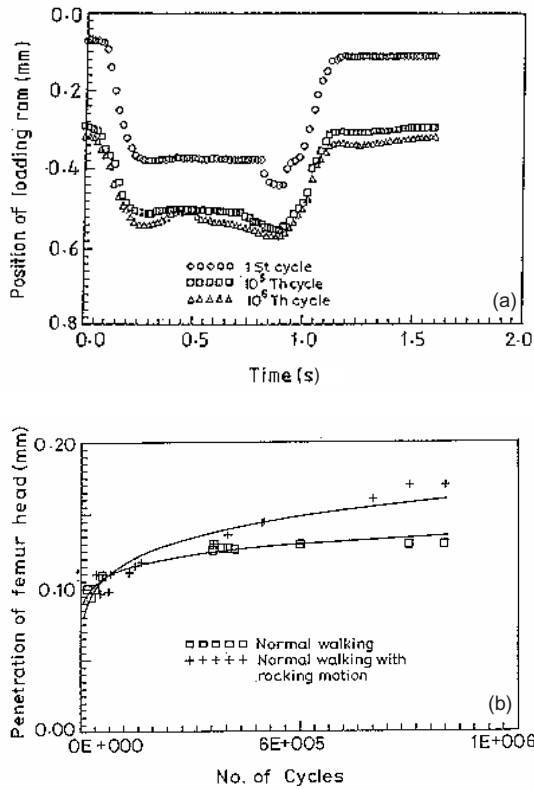


Figure 7. Penetration of the ceramic head into the acetabular cup.

weight) showed slight reduction and this became more prominent as the duration of the test increased (figure 8). Indeed, in these cases, the stress intensity factor inside the body was marginally higher than the threshold value, resulting in slow crack growth within the system. In this case after 10⁷ walking cycles the average fracture strength of the fatigued heads was found to be reduced to 35 ± 4 kN. However, considering the fact that the weight of a human body is hardly ever over 250 kg, the lifetime of these heads would be quasi-infinite in actual operation.

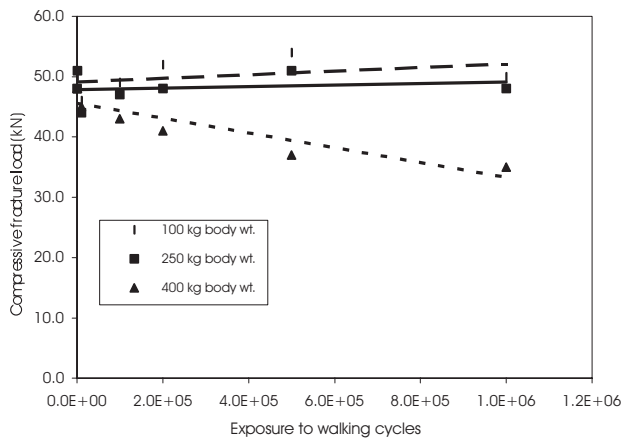


Figure 8. Fracture strength of the ceramic heads after being exposed to walking cycles of varied conditions.

Since, it was impractical to test alumina heads with such high maximum walking loads that result in fatigue failure, it was not possible to construct Wohler's curve, which represents the number of cycles for rupture corresponding to a particular maximum stress. However, the results showed that for very high loads (≈ 17.2 kN), there was substantial sub-critical crack growth and therefore it becomes essential to design a proof test for these alumina heads to correspond to a particular fatigue life in an identical condition.

Assuming a patient of 400 kg body weight takes 2.5×10^6 steps per year and altogether 10^8 steps in 40 years, the service life of these femoral heads can be estimated with the help of (3). The constants for the equation as determined by separate experiments were found to be as follows.

$A = 1.8 \cdot 10^{-26}$, $Y = 1.2115$, $K_{1c} = 4.2 \text{ Mpa} \cdot \text{m}^{1/2}$, $n = 30$, while the maximum stress at point C (figure 6) of the ceramic head was estimated as 250 MPa by finite element analysis for a person of 400 kg body weight (17.2 kN load at the point C of the femoral head). Putting these values in (3), it was estimated that to provide a fatigue life of more than 40 years the alumina heads should have cracks below a specific dimension and the capacity to withstand a compressive load of 30 kN. Therefore, a proof test needs to be introduced to check the reliability of the performance of these heads when a sudden compressive load of 30 kN is imposed on them. The heads that pass the test conditions would definitely serve for at least 40 years in a patient of 400 kg body weight. However, this value needs to be further verified as (3) is an over-simplified relationship and is applicable mainly for static/cyclic loading.

4. Conclusions

- (1) Prototypes of alumina-made femoral heads withstood all the test parameters for 10^7 test cycles and did not fail even at the maximum walking stress of 17.2 kN which is equivalent to a body weight of 400 kg.
- (2) There was no sub-critical crack growth in the alumina heads for the maximum walking load of 10 kN, which indicates quasi-infinite performance life in patients up to a body weight of 250 kg.
- (3) A proof test was designed for testing of the ceramic heads to provide a safe performance life of at least 40 years in the patients with 400 kg body weight and all the heads of the present investigation passed through that test proving the high reliability of the material.

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