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The influence of loading conditions on the life-times in fatigue testing of bone cements

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The fatigue behaviour of bone cement was investigated with respect to the influence of loading conditions. The tests were performed under simulated physiological conditions using a testing arrangement in accordance with ISO. A pure load-controlled and pure displacement-controlled cycling procedure were compared. It is demonstrated that load control is much more critical and leads to decisively shorter life-times, or remarkably lower long-term strengths. In consequence, in order to determine reliable material properties for life-time predictions and safety assessments, it is necessary to measure the fatigue behaviour under load control as this corresponds to the normal physiological situation.

1. Introduction

Since the long-term strength under alternating loads determines the durability of an implant fixation by bone cement, fatigue testing can be a decisive means to ensure the reliability of a cement for *in vivo* applications. This has been demonstrated in the past by a number of investigations and by several authors [1, 2]. Unfortunately, the test conditions of these studies differ strongly with respect to the testing setups and load applications, the specimen sizes and shapes, the frequencies and the environmental conditions. Frequently, displacement-controlled procedures are preferred because they are easier to apply and less expensive than load controlled procedures. Thus, the results are generally not directly comparable.

Thus, it has been recognized that a standardized testing procedure [2, 3] is necessary. One proposal was to use the four point bending device in accordance with ISO [4], to simulate the physiological environment by Ringer's solution at 37 °C and approach the "walking condition" by a sinusoidal load of 5 Hz [3, 5, 6]. Furthermore, it was claimed necessary to perform the tests under load control, which corresponds better to the normal physiological situation.

All these presumptions have to be checked with respect to the *in vivo* situation. In this study the influence of different loading conditions, load or displacement controlled, was investigated.

2. Material and methods

From one batch of a bone cement material a large number of bar-shaped specimens (75 mm × 10 mm × 3.3 mm) corresponding to the ISO-recommendations [4] were prepared and stored at 37 °C in Ringer's solution for at least 1 month. During this period a specific moisture concentration of more than 95% is achieved to simulate the situation after a long period in the body.

The strength behaviour was characterized by four point bending tests in accordance with ISO. At first the quasistatic strength was determined by applying the load at a constant rate of 1100 N/min until fracture. From a batch of eight specimens the mean value and the standard deviation were determined. They were 72 ± 2 MPa, and serve as a reference value for the fatigue tests.

The fatigue behaviour was investigated following Wöhler's procedure by applying a sinusoidal pulsating loading at a frequency of 5 Hz. At different constant load or displacement amplitudes, the number of cycles until fracture was measured. In the case of survival after 10^7 cycles the test was stopped without failure. All tests were performed at 37 °C in Ringer's solution.

3. Results

Fig. 1 shows the data obtained during load control, i.e. the upper limit of the applied cycling force was kept constant during the test. The fatigue data are represented by crosses for the fractured specimens and circles for the surviving specimens. These data are fitted by a line obtained by linear regression in this semilogarithmic graph. For orientation, the quasistatic values are depicted at 1 cycle. Both sets, quasistatic and dynamic, are connected by a second line to indicate the global course.

Fig. 2 shows the data obtained under displacement control, i.e. in this case the upper limit of the deflection was kept constant. The data are depicted in a similar way to Fig. 1. For the sake of comparability, however, the measured values are not plotted at the corresponding constant displacement levels, but at the levels of maximum stress which is reached during the first few cycles.

In Fig. 3 the results for the two loading conditions are compared. For easier evaluation only the regression lines for the fatigue data are depicted in this

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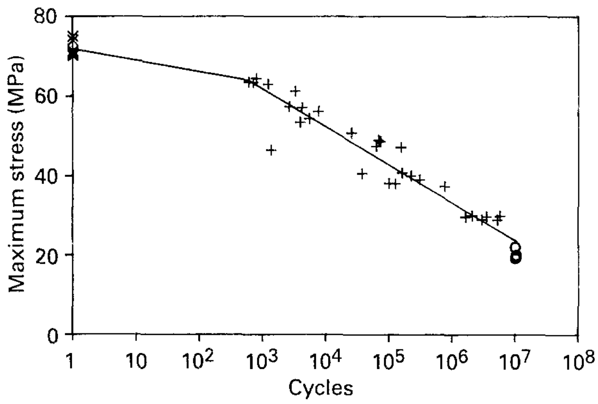

Figure 1 Strength and stress-cycle data under load-controlled conditions.

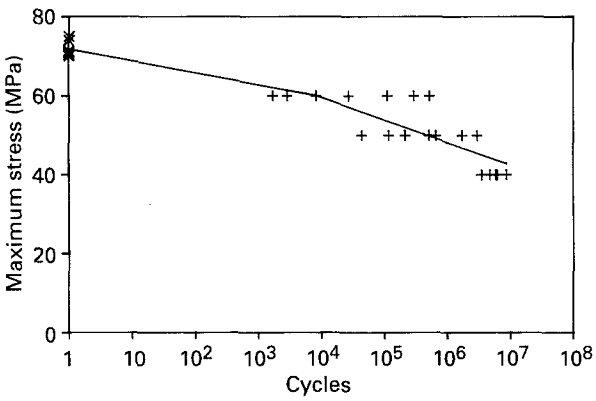

Figure 2 Strength and stress-cycle data under displacement-controlled conditions.

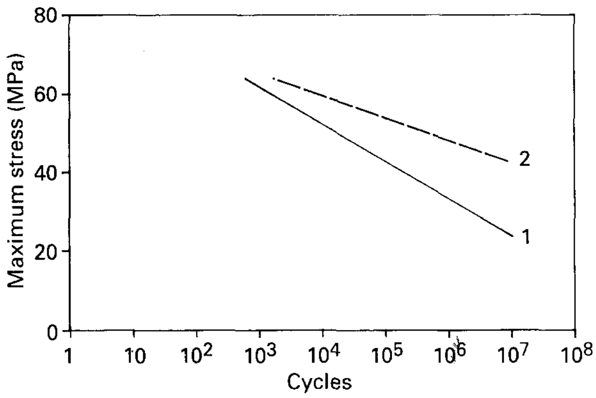

Figure 3 Comparison of the stress-cycle curves for load (1) and displacement (2) control.

diagram. It is obvious that the material is subjected to a distinct decrease in strength with increased load cycling. This decrease, however, strongly depends on the loading conditions.

After 10^7 cycles, which corresponds to about to 3–5 years walking, the strengths differ by nearly a factor of 2, or, considering the results from the aspect of life-times: for a given load level they can vary by a factor of 100.

4. Discussion

This completely different behaviour is due to the fact that under load control the stresses remain constant

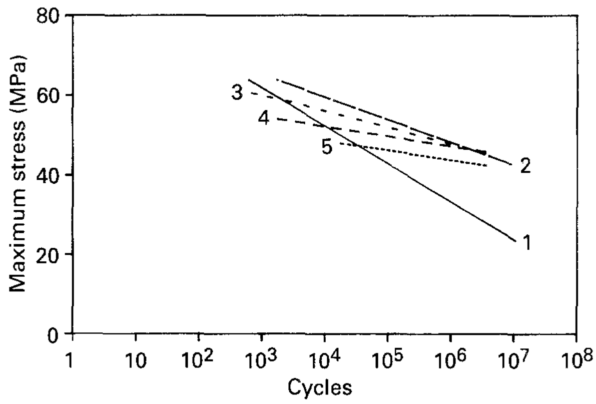

Figure 4 Comparison of the stress-cycle curves obtained by assuming different loading levels (3–100 cycles; 4–1000 cycles; 5–10 000 cycles). Graphs 1 and 2 are as for Fig. 3.

during the whole test, whereas under displacement control the stiffness of the specimen falls off due to creep and crack extension and thus, the stresses decrease in a similar way. This means that displacement-controlled testing is much less critical with respect to failure behaviour. It might even be dangerous because it underestimates the risk of fracture and, thus overestimates the life-times considerably.

It might be argued that this difference is only of academic interest and of no importance for real experimental procedures because under displacement control the load usually is, or can be, adjusted to the starting value so that more or less a load control is realized. In order to check this assumption an attempt was made to evaluate the tests also at these conditions. The displacement-controlled data were additionally plotted not only at the load level of the starting cycles, but also at load levels which are obtained after 10^2, 10^3 and 10^4 cycles. This is similar to a later adjustment of the load to these levels after the number of cycles considered, however, it represents an even more critical condition than a subsequent raising to the starting level. It should shorten the life-times because the loads before that are even higher.

The regression lines obtained for these evaluations are shown in Fig. 4. It is true that the curves are shifted to lower strengths and shorter life-times as predicted, but, particularly in the long-term range, the effect is small and the values cannot be considered to be representative of the load-controlled procedure.

4. Conclusions

These findings clearly demonstrate the necessity for testing the fatigue behaviour of bone cements under load-controlled conditions in order to assure a more reliable and safer prediction of life-times. This statement is valid, moreover, for most applications of biomaterials and implants in general because most of the physiological processes run load-controlled.

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