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The static and cyclic strength of a bone–cement bond

S. ISHIHARA, T. GOSHIMA
Department of Mechanical Engineering, Toyama University, Toyama, 930-8555, Japan
K. KANEKASU
Department of Orthopedic Surgery, Saiseikai-Takaoka Hospital, Takaoka, 933, Japan
A. J. MCEVILY
Metallurgy Department, University of Connecticut, Storrs, CT 06269, USA

Four-point bending static and fatigue tests were carried out on bone–cement bonds. The effects of the pressurization and the washing of the bone joint face on the bond strength were investigated. The results are summarized as follows. When the bond surface of cancellous bone is washed prior to the application of the bone cement, both the static and fatigue strengths of the bond are increased relative to the corresponding properties of unwashed bone–cement bonds. From observations of bone–cement interfaces as well as the fracture surfaces of bone–cement specimens, it has been determined that bone cement was able to infiltrate into fine holes present in washed cancellous bone. However, such infiltration occurred to a much lesser degree in the case of unwashed cancellous bone. Increasing the molding pressure during the time of cement application to the bone from 39200 to 117600 Pa had a beneficial effect on the bending strength and fatigue properties, particularly in the case of washed bone cement specimens. An increase in molding pressure also resulted in a reduction in the amount of scatter in test results.

1. Introduction

The strength and durability of a surgical implant depends on the quality of the interfaces between implant and bone. The outer and inner parts of bone consist of cortical bone and cancellous bone, respectively, with the strength of a joint being determined in part by the nature of the bond established between bone cement and the microstructure of the cancellous bone. The state of stress in a bone–cement bond is complex not only due to the nature of the bond itself but also due to the differences in Young's modulus and Poisson's ratio of the two constituents. In addition, factors such as surface tension, capillarity and viscosity are important in determining the penetrability of the bone cement into porous regions within bone. It has also recently been recognized that surgical technique often controls the performance of artificial joints [1, 2]. Research is therefore needed that can lead to improvements in surgical technique in order to optimize the quality of the interface between bone–cement and cancellous bone. Some related research, which deals with the fracture toughness, and fatigue crack growth resistance of cement has been carried out by Mak and Lewis [3], Lewis *et al*. [4], and Gates *et al*. [5]. The present research adds to this information by providing information concerning the fatigue resistance of bone–cement joints.

In the present study, static bending tests and four-point bending fatigue tests have been carried out on specimens composed of bovine cancellous bone and epoxy bone cement. Two cement application techniques were investigated. One dealt with the effect of washing of the bone prior to application of the cement, the other with the effect of applied air pressure while bonding cement to the bone.

2. Specimens and experimental procedures

2.1. Specimens

Two epoxy bone cements, CMW Type 3 and ZIMMER, were used to investigate the effect of the type of cement on the quality of the interface between cement and cancellous bone. CMW Type 3 bone cement is made by the Laboratories Company, and ZIMMER bone cement is made by the Bristol-Myers Squibb Company. In the following, these bone cements will be simply designated as CMW and ZIMMER. The chemical compositions and mechanical properties of both cements are shown in Tables I and II, respectively. It is noted that the bending strength and fracture toughness of CMW are higher than that of ZIMMER.

Fig. 1 shows the method used in specimen preparation. A cancellous bone fragment was removed from a bovine femur, with the length direction of the bone fragment parallel to the longitudinal direction of the bovine femur.

TABLE I Chemical compositions of the bone cements, CMW and Zimmer

	CMW	ZIMMER
	Methyl methacrylate	Methyl methacrylate
Powder	Barium sulfate	Barium sulfate
	Benzoyl peroxide	Benzoyl peroxide
Liquid	Methyl methacrylate	Methyl methacrylate
	N,*N*-Dimethyl-*p*-toluidence	*N*,*N*-Dimethyl-*p*-toluidence
	Hydroquinone	Hydroquinone
	Ascorbic acid	
	Ethyl alcohol	

TABLE II Mechanical properties of the bone cements, CMW and ZIMMER

	CMW	ZIMMER
Young's modulus (GPa)	2.69	2.92
Bending strength (MPa)	57.67	48.65
Fracture toughness ($MPam^{1/2}$)	2.22	2.14

This bone fragment was then finished into a specified specimen form and polished with emery papers. Two types of final surface finish for these bone fragments were used. Either the bone fragments had a machined and polished joint surface (denoted as unwashed material), or the joint surface was washed after polishing (denoted as washed material). The washing process consisted of lightly brushing the surface to be bonded while it was immersed in water.

Fig. 2 shows the microstructure of cancellous bone in both the washed and unwashed conditions. In the washed material, Fig. 2(b) many pores in the cancellous bone structure are obvious. On the other hand, in the unwashed material of Fig. 2(a), naturally occurring biological materials completely fill these pores.

In order to bond the bone cement to the bone specimen, a cancellous bone fragment was placed into one half of a steel mold, and freshly mixed bone cement which had been prepared in accord with the manufacturer's recommendations, was then poured into the other half of the mold. The two halves were then put together and immediately transferred into a sealing container in order to bind the bone cement to the cancellous bone under air pressure of either 39 200 or 117 600 Pa. The pressurization time was 10 min. The specimen was then removed from the mold and finished by grinding to the final form shown in Fig. 3.

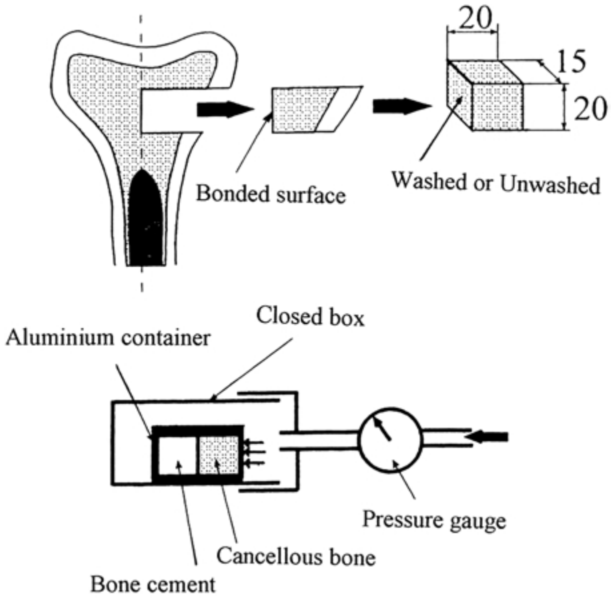

Figure 1 The specimen preparation method.

2.2. Experimental methods

A tension-compression testing machine was used for the static four-point bending tests where the inner and outer spans were 10 mm and 30 mm, respectively. In these tests the crosshead speed was 0.5 mm/min. A servo-hydraulic fatigue testing machine was used for the fatigue tests. Four-point bending fatigue tests were carried out using the same inner and outer spans as in the static tests at a frequency of 1 Hz, a stress ratio $R = 0.1$, and sine-wave loading. In order to simulate an *in vivo* environment, Ringer's solution at a constant temperature of 310 K, the same as in the human body, was dripped upon the specimen surface throughout the fatigue experiments. Observations of the cement–bone interface and of the fracture surfaces of the specimens were made with an optical microscope.

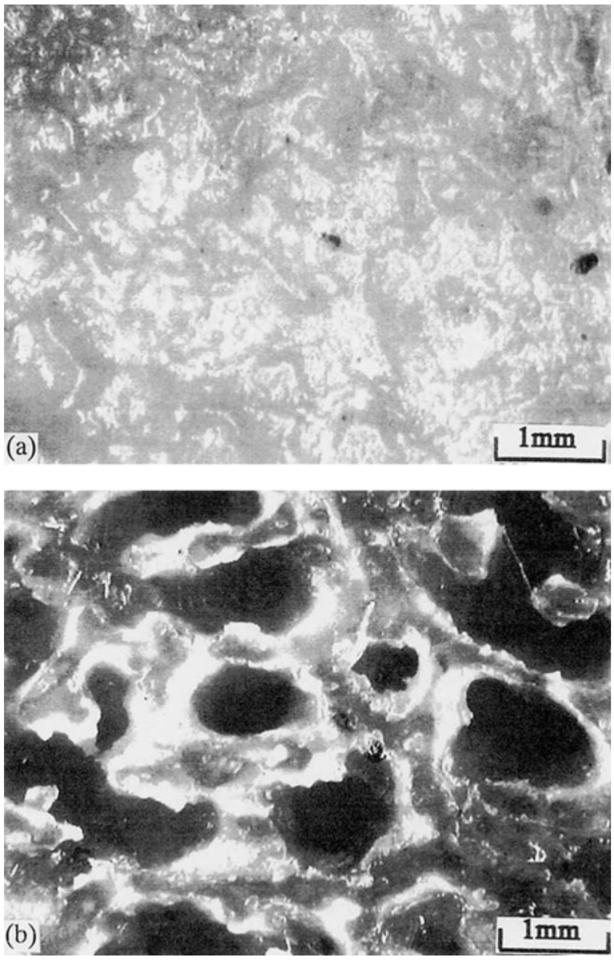

Figure 2 The microstructures of cancellous bone for both (a) the unwashed and (b) washed conditions.

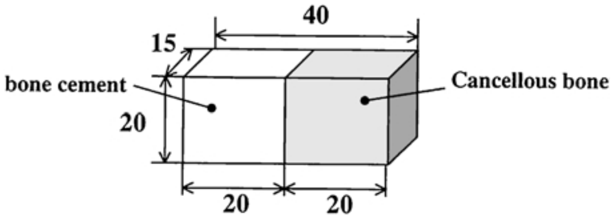

Figure 3 Shape and dimensions of the cement-bone specimen.

TABLE III Weibull parameters for U-S-CMW and W-S-CMW

	$P = 39\,200$ (Pa)	$P = 117\,600$ (Pa)
U-S-CMW		
Scale parameter, x_0	2.3	9.8
Shape parameter, m_0	0.81	1.57
W-S-CMW		
Scale parameter, x_0	2.4×10^2	3.6×10^5
Shape parameter, m_0	2.12	4.25

3. Experimental results

To designate the type of bond surface of the cancellous bone (whether unwashed or washed), the type of test (whether static or fatigue), and type of bone cement the following system will be used:

U-S-CMW = unwashed bone-static test-CMW cement
W-S-CMW = washed bone-static test-CMW cement
U-F-CMW = unwashed bone-fatigue test-CMW cement
W-F-CMW = washed bond-fatigue test-CMW cement
W-F-ZIMMER = washed bone-fatigue test-ZIMMER cement

3.1. Static bending strengths

U-S-CMW and W-S-CMW bending strengths were determined. Because a large scatter in bond strength was expected due to the inhomogeneous nature of the interface between bone and cement, a statistical analysis of the bending strengths was investigated using 10 specimens. The Weibull distributions for U-S-CMW and W-S-CMW are shown in Fig. 4. In this figure, the molding pressure, either 39 200 Pa or 117 600 Pa is indicated. The statistical distribution of the bending strengths was approximated by a two-parameter Weibull distribution, with the values of the shape and scale parameters being determined by the least-square method. The values of these parameters for U-S-CMW and W-S-CMW are listed in Table III.

Fig. 4 and Table III both show that the bending strength of washed specimens substantially higher than that of unwashed specimens. The bending strength of washed specimens ranged from 9 to 20 MPa, whereas the bending strengths of unwashed specimens ranged from 0.5 to 10 MPa. Also, the shape factor for washed specimens was higher than for unwashed, an indication of lesser scatter. Furthermore, the beneficial effect of an increase in molding pressure is more pronounced in the case of washed specimens as compared to unwashed specimens. Therefore, a substantial improvement in the bending strength is obtained by the washing of the cancellous bone bond-surface as well as by increasing the molding pressure.

3.2. Fatigue strength

3.2.1. U-F-CMW and W-F-CMW test results

S–N curves for U-F-CMW and W-F-CMW are shown in Figs. 5 and 6. In these figures the molding pressure is indicated. In addition, an S–N curve for unwashed cancellous bone is also shown in Fig. 5. It is seen from Fig. 5 that for U-F-CMW an increase in molding pressure had a beneficial effect on fatigue behavior, particularly at the lower stress amplitudes. It is also noted that the fatigue lives of the bone–cement specimens are shorter than those of plain cancellous bone. The bonding process therefore has had a deleterious effect on fatigue resistance.

Fig. 6 indicates that the fatigue lifetimes were increased by a factor of about three by washing the bond face, a substantial increase. This increase is even larger than that obtained by increasing the molding pressure. Since a similar trend was also found in the experimental results for the static bending tests it is clear

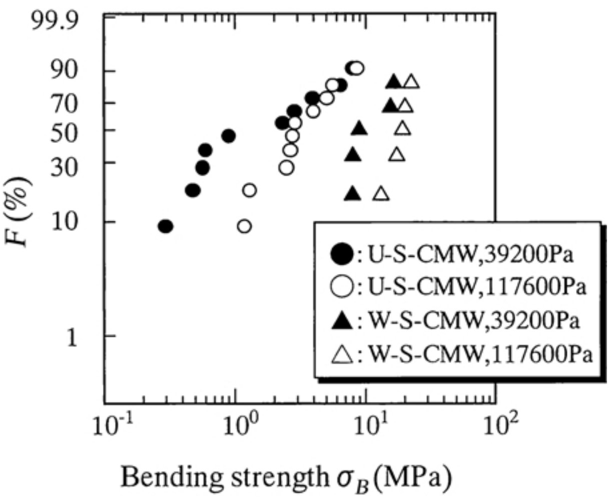

Figure 4 The Weibull distributions of static bending strengths for U-S-CMW and W-S-CMW.

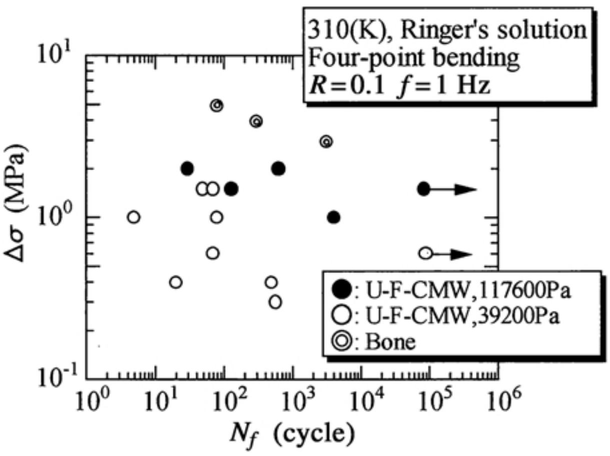

Figure 5 S–N curves for U-F-CMW and bone.

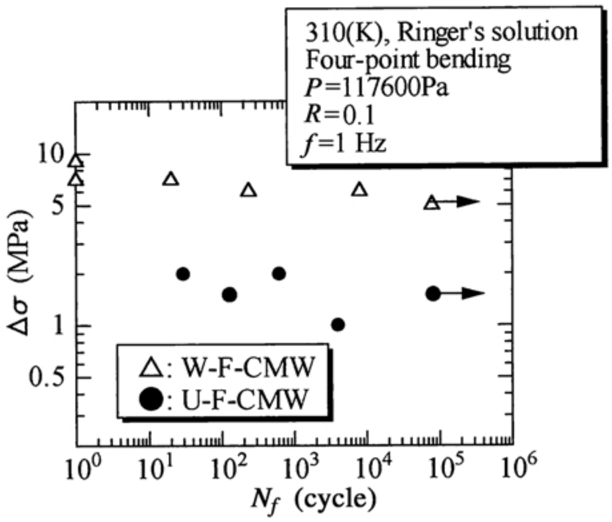

Figure 6 S–N curves for U-F-CMW and W-F-CMW at a molding pressure of 117 600 Pa.

that it is important to properly wash the bone bond face at the time of an operation.

3.2.2. Comparison W-F-CMW and W-F-ZIMMER test results

S–N curves for W-F-CMW and W-F-ZIMMER are shown in Fig. 7 for specimens prepared at a molding pressure of 117 600 Pa. It is seen that at the same stress amplitude, the fatigue life of W-F-ZIMMER is less than that of W-F-CMW.

3.3. Observations of the bond interfaces and fracture surfaces

3.3.1. Morphology of the joint interface

Photographs of the bone–cement joint interface of the specimens prepared with molding pressures of 117 600 Pa are shown in Fig. 8. Fig. 8(a) and (b) are for washed and unwashed specimen, respectively. As seen in these figures, in the case of the washed specimens, the bone cement infiltrated into the fine holes within the

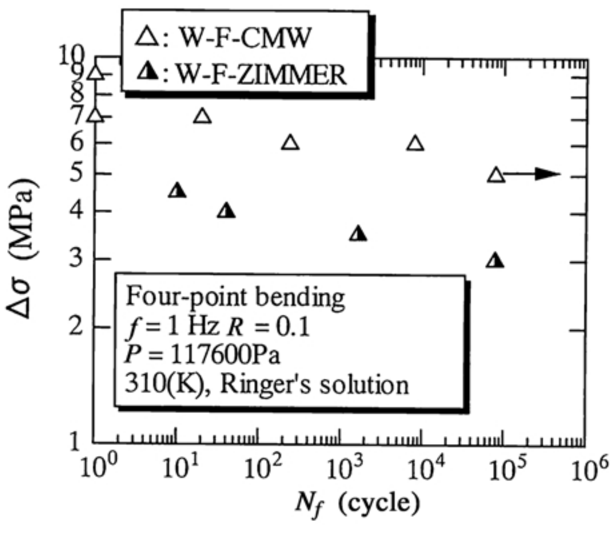

Figure 7 S–N curves for W-F-CMW and W-F-ZIMMER for specimens prepared at a molding pressure of 117 600 Pa.

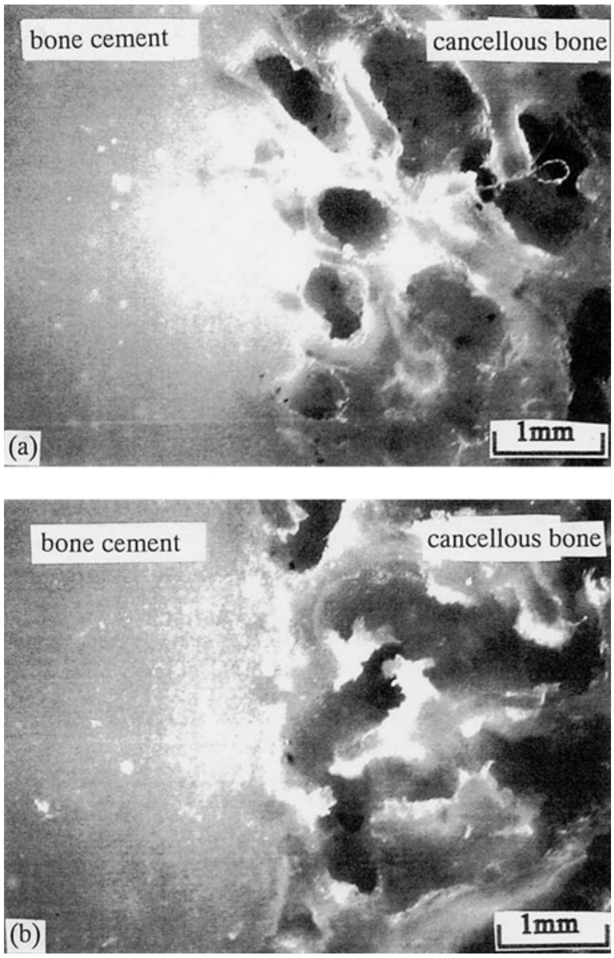

Figure 8 Photographs of the bone–cement joint interface of the specimens prepared with molding pressures of 117 600 Pa. (a) for washed specimen, (b) for unwashed specimen.

cancellous bone, thus leading to a good bond between bone cement and bone. In the unwashed material, a much lesser degree of infiltration was obtained. This lack of infiltration was due to the fact that the pores in the unwashed specimens were filled with biological material, which prevented the infiltration of the bone cement. As a result the bonding between cement and bone was much poorer in the case of unwashed specimens as compared to washed specimens. It was also noted that there was no obvious influence of the molding pressure level on the degree of infiltration of the bone cement, even though an increase in molding pressure was found to improve both static and fatigue properties.

3.3.2. Fracture surfaces of specimens ruptured under static bending

The fracture path under static bending either followed the interface between bone and cement (U-S-CMW), or was in the bone close to the interface between bone and cement (W-S-CMW). Figs. 9 and 10 show the fracture appearance for the bone side of the bond and the cement side of the bond, respectively, for specimens prepared under a molding pressure of 117 600 Pa. Figs. 9(a) and 10(a) are for W-S-CMW, and Figs. 9(b) and 10(b) are for U-S-CMW. In Fig. 9(a), which shows the fracture surface of cancellous bone for W-S-CMW, the bone cement that

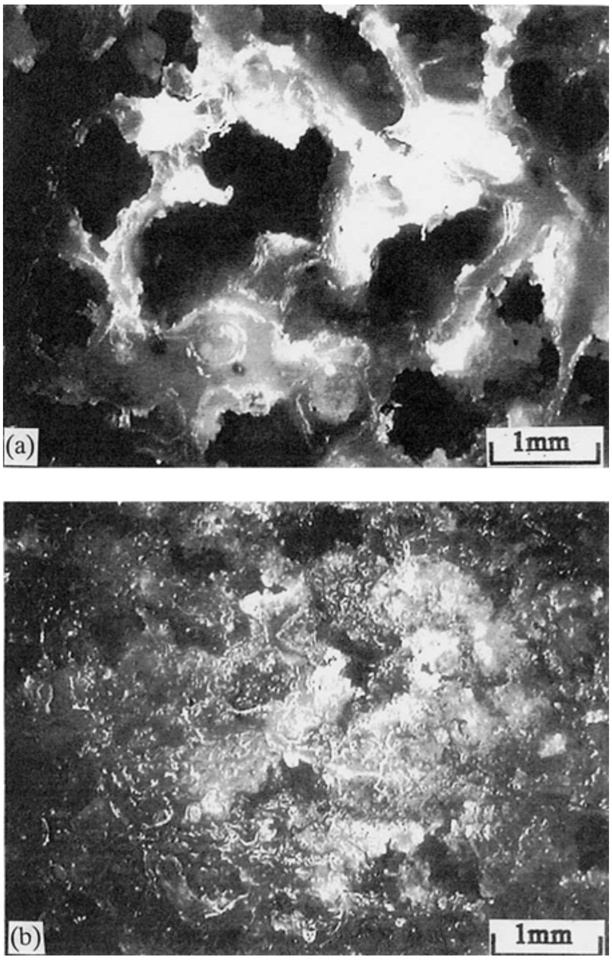

Figure 9 Fracture appearance for the bone side of the bond. (a) W-S-CMW, (b) U-S-CMW.

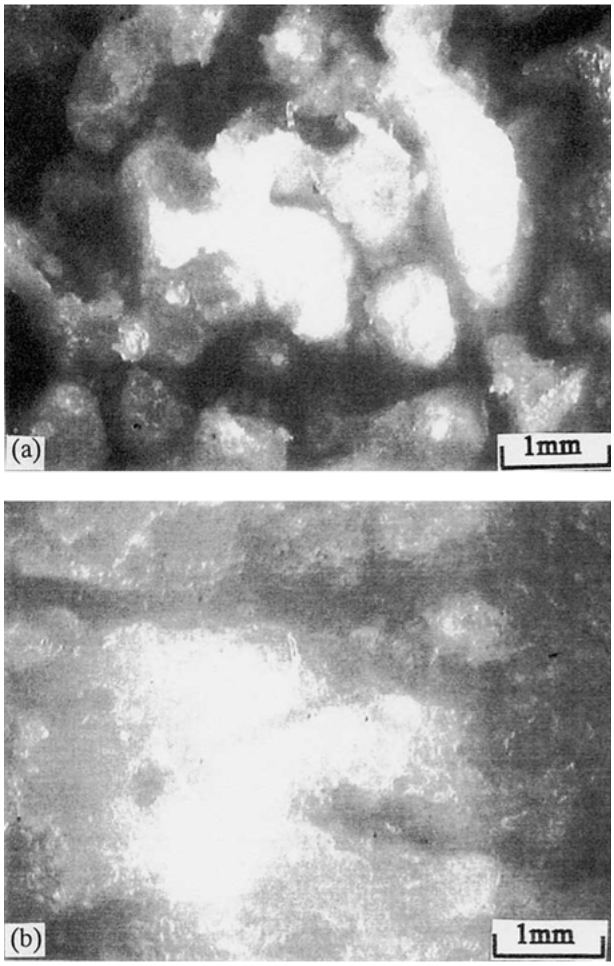

Figure 10 Fracture appearance for the cement side of the bond. (a) W-S-CMW, (b) U-S-CMW.

penetrated into the fine pores in the bone during bonding has been left in the pores after fracture. In Fig. 10(a), the fracture surface on the cement side of the bond of W-S-CMW contains many asperities, indicating that the fracture path was through the bone due to infiltration of bone by the cement and a good bond between bone and cement. These observations indicate that in the washed material sufficient amount of the bone cements entered into the fine holes of a cancellous bone. On the other hand, in the case of U-S-CMW, very little bone cement entered into the bone pores and fracture was along the interface between bone and cement, as seen in Figs. 9(b) and 10(b). It was also noted that the molding pressure had little effect on the appearance of the fracture surfaces.

3.3.3. Crack growth path during the fatigue process

Fig. 11 provides two examples of the fracture at the specimen interface for W-S-CMW after four-point bending fatigue tests of two specimens, both tested at the same stress amplitude. Fig. 11(a) is for a specimen with a short life, and Fig. 11(b) is for specimen with a long life. In the short life specimen, the crack mainly propagates along the bone–cement interface, whereas in the long life specimen the crack propagated in the cancellous bone very close to the bone–cement interface. When a strong bond developed between the cancellous bone and the bone cement, the crack path was primarily in the bone rather than the interface, and the fatigue life of such a specimen was relatively long compared to the lifetime of a specimen, which failed in the interface.

4. Discussion

4.1. Effect of washing of the bone's bond face on the bond strength

The results presented above show that the static bending strength and the fatigue strength of the bone–cement bond both improve with increase in molding pressure and with washing of the bone's bond face. Better contact between bone and cement may be obtained by increasing the molding pressure, but greater depth of infiltration was not observed on going from 39 200Pa to 117 600 Pa. Washing the bone bond surface was effective in removing biological matter from the pores which facilitated the infiltration of the bone cement. It is noted that the improvement in bond strength due to pressurization was less than that obtained as the result of washing.

4.2. Comparison of the fatigue strengths between CMW and ZIMMER joint

From the observation of the fracture surface, bone cement had penetrated into the exposed pores of the

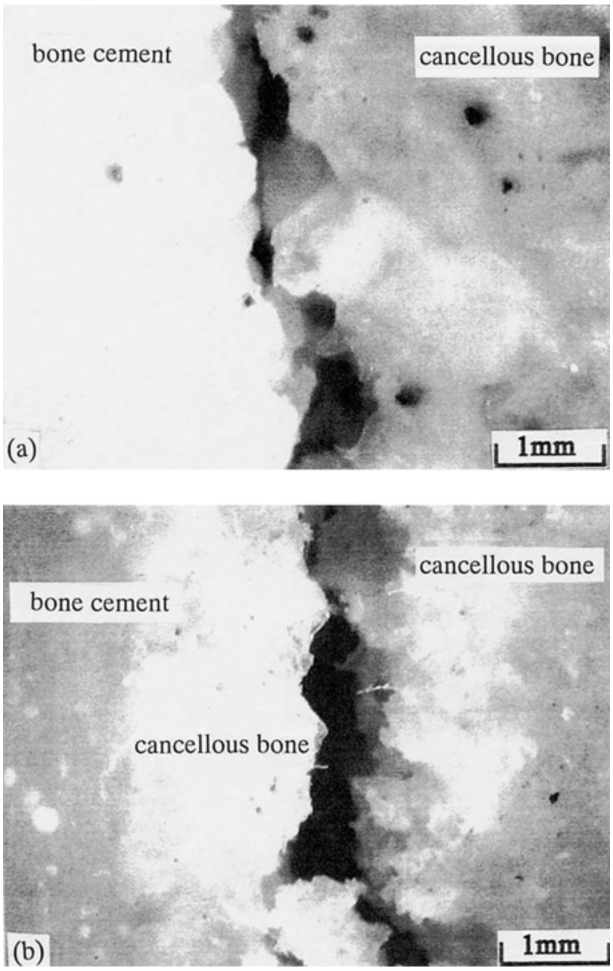

Figure 11 Two examples of the fracture at the specimen interface for W-S-CMW after four-point bending fatigue tests of two specimens, both tested at the same stress amplitude. (a) for a specimen with a short life, (b) for specimen with a long life.

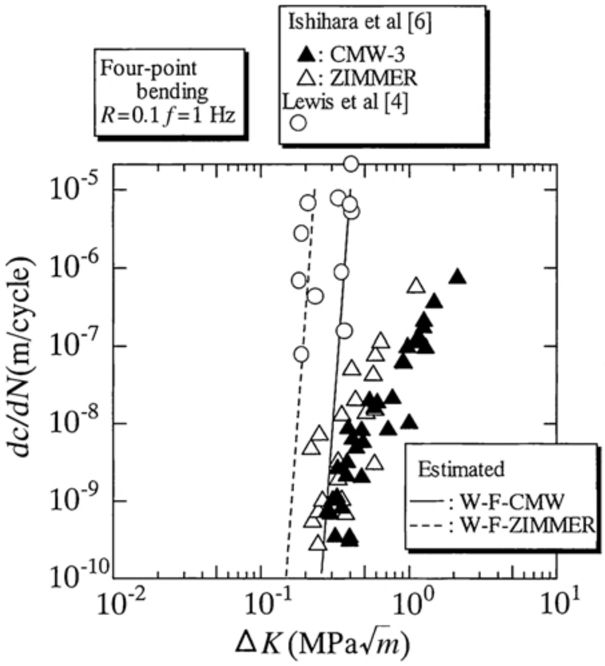

Figure 12 The estimated relationship between crack growth rate and stress intensity factor for both the CMW and ZIMMER joints.

cancellous bone and had been fractured during the process of fatigue crack growth. This finding indicates that the fatigue strength of the bone–cement bond may be strongly affected by the strength of the bone cement itself. Therefore, the higher fatigue strength of W-F-CMW as compared to W-F-ZIMMER may result from the higher tensile strength and fracture toughness of CMW relative to ZIMMER.

As seen from Fig. 7, the slopes of the S–N curves for the bone–cement bonds are quite low. This implies that a brittle crack growth type of behavior occurred during the fatigue process. In the following we will estimate the fatigue lives of the bone–cement bonds, based on the assumption that most of the fatigue life is spent in the crack growth period. The crack growth behavior of the bone–cement bonds is assumed to be described by Paris's power law, i.e.,

$$dc/dN = A(Y\sigma\sqrt{\pi c})^m \qquad (1)$$

where, A and m are material constants, Y is a boundary correcting factor which is assumed to be 1.122 [7] and c is the half crack length. After integrating the above expression between the limits of the initial crack size, c_0, and final crack size, c_f, the following expression is obtained for the total lifetime where we assume that the number of cycles spent in crack initiation is negligible:

$$c_f^{(2-m)/2} - c_0^{(2-m)/2} = \frac{2-m}{2} A Y^m \pi^{m/2} \sigma^m N_f \qquad (2)$$

Introducing some modifications into this expression, we can get the next relationship between stress amplitude and fatigue lives, N_f.

$$m \ln \sigma + \ln\ N_f\ =\ \ln\left\{\frac{2(c_f^{(2-m)/2}\ -\ c_0^{(2-m)/2})}{(2\ -\ m)AY^m\pi^{m/2}}\right\} \qquad (3)$$

When this expression is plotted in the log–log form, a linear relation is obtained between stress amplitude and the number of cycles to failure. We assume that this analytically obtained relation is equivalent to the experimentally obtained S–N curve, and select the parameters A and m to obtain a reasonable fit.

With these estimate values for A and m we can also compare the crack growth behavior as in Fig. 12 which shows the estimated relationship between crack growth rate and stress intensity factor for the both CMW and ZIMMER joints. In this figure, the experimentally obtained data of the bone cement [6] is also shown for a comparison, and it is noted that we are dealing with relatively low values of the stress intensity factors, a reflection of the low fracture toughness of bone–cement joints, i.e., from 0.13 to 1.33 MPa as reported by Lewis *et al*. [4], who found the lowest values of fracture toughness to be associated with pull out of the cement from the bone, and the highest values to be associated with failure in the bone. Failure in the cement was associated with an intermediate fracture toughness level.

It is of interest that the estimated crack growth behavior is similar to that obtained by Lewis *et al*. [4]. The slope of the estimated *dc*/*dN* relation for the bone–cement bond is steeper than that of the bone cement, indicating a more brittle crack growth process in the former. Next, consider the reason for the difference between the CMW and ZIMMER bonds. It was deduced that the crack growth rate of the CMW bond was less than for the ZIMMER bond. Accordingly, the difference of the crack growth behavior, especially in the low crack growth rate region may strongly result in a difference in the fatigue lives. Previous work [6] has shown that there were more small holes($< 300\,\mu m$), but less large holes($> 300\,\mu m$) within CMW bone cement than within ZIMMER bone cement. These holes may influence the crack propagation process of the CMW joint. The many small holes ahead of the main crack are expected to lower the crack-tip singularity by surrounding the tip when the crack-tip enters in the holes. So, in the CMW joint, a more toughened crack growth nature was seen than in the ZIMMER joint. The present results indicate that CMW bone cement is superior to ZIMMER bone cement for the use in an artificial joint. However, the polymerization temperature of the ZIMMER bone cement is lower by 20 K than that of CMW. Such a lower temperature would have a beneficial effect on living body tissue. Therefore a variety of considerations, not simply mechanical properties, must be taken into account when deciding which bone cement should be selected for use in an artificial joint.

5. Conclusions

Four-point bending static and fatigue tests were carried out on bone–cement bonds. The effects of the pressurization and the washing of the bone joint face on the bond strength were investigated. Fatigue tests with two different bone cements, CMW and ZIMMER were also performed to compare the fatigue strengths for the both joints. The results obtained are summarized as follows:

1. When the bond surface of cancellous bone is washed prior to the application of the bone cement, both the static and fatigue strengths of the bond are increased relative to the corresponding properties of unwashed bone–cement bonds.

2. It was observed that the increase in bending and fatigue properties obtainable by washing the bone bond-surface prior to the application of cement was greater than that obtainable by increasing the molding pressure from 39 200 to 117 600 Pa.

3. From observations of bone–cement interfaces as well as the fracture surfaces of bone–cement specimens, it has been determined that bone cement was able to infiltrate into fine holes present in washed cancellous bone. However, such infiltration occurred to a much lesser degree in the case of unwashed cancellous bone.

4. Increasing the molding pressure during the time of cement application to the bone from 39 200 to 117 600 Pa had a beneficial effect on the bending strength and fatigue properties, particularly in the case of washed bone cement specimens. An increase in molding pressure also resulted in a reduction in the amount of scatter in test results.

5. The fatigue strengths of bone–cement bonds made with ZIMMER cement were lower than those made with CMW cement.

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