Ultrasonic Techniques for the Assessment of Aging and Damage Accumulation in PMMA Cement and Cement/Metal Interfaces

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Introduction: In order to quantify the failure mechanisms related to the loosening of cemented hip joint replacements, novel techniques have been developed that are capable of monitoring, non-destructively, the initiation and progression of failure during in vitro fatigue tests and the effect of aging on the mechanical properties of cement materials. Fatigue testing of model cement-stem test pieces was carried out using multi-axial fatigue testing machines and acoustic emission (AE) sensors were employed to detect onset of damage. Once damage was detected, an ultrasonic imaging system was used to obtain an image of the damage site. This method of examination provides detailed insight into the crack propagation and delamination mechanisms, hitherto unobtainable during fatigue testing.

Method and Discussion: CMW-1 radiopaque bone cement (DePuy/CMW, UK) was used throughout the experiments. The cement was vacuum mixed using the VacuMix system (DePuy/CMW, UK. The work on the ultrasonic characterisation of the PMMA/stainless steel specimens was conducted in three parts: (i) effect of aging on PMMA (ii) imaging of defects in PMMA mantle specimens (iii) imaging of defects at the cement/substrate interface. The first phase of the work was on the investigation of the effects of aging on the mechanical properties of PMMA, as measured using two ultrasound propagation characteristics over a period of 54 days. Compressional wave velocity and attenuation were measured on 8 specimens of PMMA that were aged in a physiological solution at 37^{o}C. Both these parameters were measured at 14 day intervals on all 8 samples. The correct trends in the measured velocity and attenuation were observed since the ingress of moisture is expected to decrease the velocity and increase the attenuation. Two types of mantle specimen were used for the second phase of the work. The first had been subjected to bending fatigue and AE signals were collected during fatiguing. These specimens showed a significant degree of variation in the distribution of defects imaged using a high frequency ultrasonic imaging system. Figure 1 shows an example of images obtained for a specimen were many cement mantle defects could be seen. The number of defects increased with time, and could be correlated with the acoustic emission location data. High resolution images were also obtained for a cement specimen subjected to tensile loading. The defects in this case have been imaged in 3-dimensions for correlation with the AE data. High frequency images obtained from the cement/substrate interface at different stages of fatigue testing of cement/steel coupons clearly show the progressive growth of an interface delamination. These results were correlated with AE signals obtained over the same region of the sample using four sensors.

Two new techniques were developed during this study for improving the sensitivity to variations of interfacial conditions. The first was a shear-wave imaging system developed with the aid of a theoretical model for calculating the reflectivity of shear waves from weak interfaces. The model predicts the optimum angle for shear wave incidence in order to maximise the sensitivity to interfacial stiffness variation. Such an image can show variations in interfacial stiffness even before gross delaminations have occurred. The second novel technique was the use of Wiener filtering and spectroscopy to obtain much sharper images of defects and reducing the ambiguity in differentiating between defects and background noise.

Conclusions: We have developed novel ultrasonic techniques for monitoring the effect of aging and imaging damage accumulation in cement and cement/metal specimens during fatigue testing. The results on aging show that given the large standard deviation in the initial values of velocity and attenuation compared with the measured changes after aging, the variations in properties due to mixing can be more significant than changes due to aging over this short period. Images of mantle and interface defects obtained during fatigue testing were well correlated with AE indications of damage propagation at the same damage sites. Ultrasonic imaging has thus been successfully used to establish the AE signature of different types of defects. This will allow AE sensors to be used with confidence in future monitoring of damage initiation and growth in the preclinical assessment of cement/stem models.

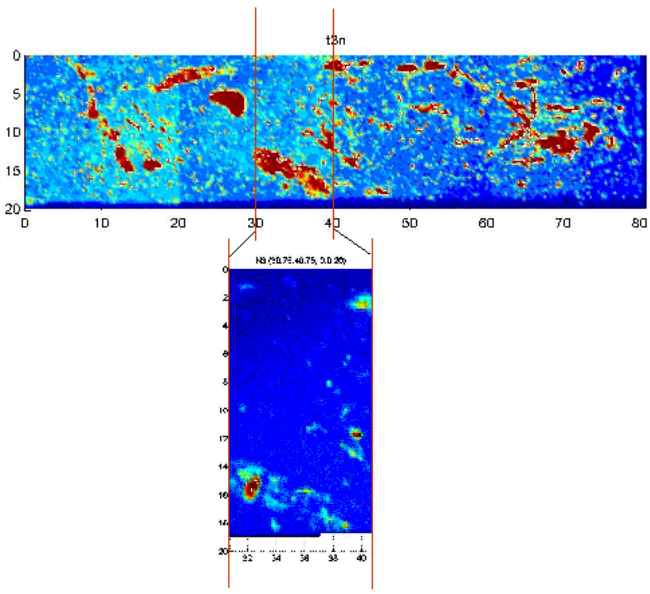

Figure 1. Accumulation of damage in bone cement - before (below) and after (above)