Effects of specimen variables and stress amplitude on the S-N analysis of two PMMA based bone cements

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ABSTRACT

The fatigue performance of bone cement is influenced by the testing parameters. In previous *in vitro* fatigue studies, different testing conditions have been used leading to inconsistencies in the findings between the studies, and consequent uncertainties about the effects of testing specimen specifications and stress parameters. This study evaluates the role of specimen variables (namely; specimen cross-section shape, surface production method and cement composition) in a range of *in vitro* stress amplitudes (±12.5, ±15, ±20, ±30 MPa), using S-N (Wöhler) analysis. The two main findings are: while specimen cross-section configuration and fabrication method (specimen type) played a key role in controlling the fatigue longevity of the same cement, the stress amplitude was seen as the dominant controlling variable to affect the fatigue behaviour of different cements when using the same specimen type. Thus, considering the effect of specimen type, testing at high stress amplitudes should be treated with caution, particularly in tension-compression loading, to ensure fatigue failure occurs due to mechanical rather than thermal effects and thus models the in vivo behaviour.

Keywords:
Polymethylmethacrylate, bone cement, stress amplitude, S-N curve, DSC analysis

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1. INTRODUCTION

PMMA based bone cements are used for the fixation of orthopaedic implants, thus their fatigue failure leads to major clinical problems in the form of implant loosening, pain and ultimately clinical failure of the device. The stress levels in the bone cement mantle around a joint replacement range from 3 to 11 MPa [1]. Depending on the patient's age and activity, a hip or a knee replacement faces up to 2 million load cycles yearly [2], therefore these stress levels are required to be transmitted by the mantle of cemented joint replacements for the rest of the patient's life, thus of the order of tens of millions of load cycles. *In vitro*, however, fatigue characterisation of bone cement has been performed using higher stress levels; mostly within the range of 10 – 30 MPa [3] to shorten testing time and reduce the number of test run-outs.

A review paper by Lewis [4] examined the "intrinsic" and "extrinsic" factors that can affect the measured fatigue performance of bone cement, concluded that there are "only a few areas of agreement" and "many areas of disagreement". The effects of specimen preparation variables (cross section shape and surface production technique) on fatigue behaviour at a specific constant-amplitude stress have been examined in previous studies considering the influence of specimen shape in tension-compression only [5], surface preparation method in tension-tension only [6] or the effects of both configuration and fabrication methods in tension-compression [7, 8] and tension-tension loading [8, 9]. Due to testing at only one stress amplitude, the fatigue data has been analysed using Weibull relationships in most of these studies [5, 7-9] and only one study [8] has compared two testing methods: tension-only of rectangular moulded specimens at a single stress level versus tension-compression at multiple stress levels of circular machined specimens analysing the results using Weibull and Wöhler approaches, respectively. Fatigue testing at various stress amplitudes has been considered in some studies, but using only a single specimen configuration and modification technique within the same study (e.g. [10-12]). It has been suggested that using different fatigue testing methods makes it inappropriate to compare the findings from different studies [13, 14]. In addition to using a range of testing conditions, it has been pointed out that many of these studies "have employed inappropriate statistical methods" [3] and "have not addressed the issue of possible interactions between the parameters being investigated" [3]. Additionally, the cement formulation [13], methods of mixing, whether or not a partial vacuum was used to reduce porosity [6, 10-12], amount and type of opacifier and/or antibiotic [13, 15], all effect the fatigue life and have been extensively discussed [e.g. 15].

Currently, various standards are available for the fatigue testing of bone cement and have been used to various extents. ATSM F2118 was originally published in 2001, with various subsequent revisions, leading to ATSM F2118-14 being the current version [16]. This standard uses cylindrical dumbbell samples, with fully reversed fatigue in phosphate buffered saline, either three stress levels are used, or the fatigue life for 5 million load cycles is found. The frequency is required to be constant and if above 5Hz should be checked to ensure that no frequency effects occur. The suggested stress levels are ±15, ±12.5 and ±10MPa which can be varied for hip and knee replacement applications or reduced to ±5, ±7 and ±9MPa for spinal applications with a minimum of 15 samples used per load level. The samples should be manufactured by injecting into a silicone mould which has been produced by moulding the silicone around machined metal blanks. The other major fatigue of bone cement standard is ISO 16402:2008 which was reconfirmed in 2013, and uses four point bending of rectangular bars [17]. The four point bending loads are from 5N to the force which produces the required maximum stress. The samples have moulded top and bottom surfaces and the sample sides may be either moulded or machined. So both standards require that the loaded surfaces are moulded, rather than machined. However, over the years many studies have used machined surfaces and particularly for cylindrical dumbbells it is easier to mould cylinders and then machine to shape. Furthermore, being fully reversed tension-compression ATSM F2118-14 [16] leads to all areas of the cement undergoing the full stress range in both tension and compression, while the 4 point bending in ISO 16402:2008 [17]means that only the upper and lower surfaces are exposed to the maximum stresses and undergo either only tensile or only compressive loading, which may not be what occurs in vivo.

However, as both machined and moulded surfaces and rectangular and circular cross-sections have been used it is important to examine the influence of specimen preparation method on more than one cement and one stress level [7, 9]. This requires the comparison of the fatigue performance of different specimen types at various stress amplitudes and examining whether testing specimen variables, along with changing the stress amplitude, can affect the fatigue behaviour of different specimens and cements and their relative ranking.

Hence the aim of the current study is to compare the fatigue results, with different sample surface preparation methods and shape, of two different bone cement formulations with the same viscosity classification (high viscosity) but different filler content. The fatigue life results are compared by the commonly used S-N (Wöhler) analysis (e.g. [8, 12, 18, 19]) as recommended in ASTM F2118-14. Furthermore, it has been reported that fatigue damage accumulation *in vivo* shows that failure progress is affected by the stress amplitude, thus using a single stress amplitude would be a "misleading measure of durability" [20].

2. MATERIALS AND METHODS

2.1. Materials

Two brands of high viscosity bone cements were tested: SmartSet GHV Gentamicin and DePuy CMW1 (both produced and supplied by DePuy CMW, Blackpool, UK). The powder component of SmartSet GHV is a methyl methacrylate/methyl acrylate copolymer and contains 14.37wt% zirconium dioxide as radiopaque agent and 4.22wt% Gentamicin as antibiotic filler whereas the CMW1 polymeric powder is solely polymethylmethacrylate and contains 9.1wt% barium sulphate as a radiopacifier with no antibiotic added. The liquid component is similar for these two cements. A detailed comparison of these cements is available in an earlier study [7].

2.2. Preparation and testing of specimens

The powder and liquid phases were mixed under vacuum using the CEMVAC mixing system (DePuy CMW, Blackpool, UK) as per the manufacturer's instructions, using the recommended mixing, waiting and working time for each cement type, dependant on the room temperature (20±2°C). Test specimens were manufactured to produce either half-sized ISO 527-2 [21] specimens with rectangular cross sections of 4mm by 5mm (designated R), or ASTM F2118 [16] to produce 5mm diameter circular cross section samples (designated C), thus similar nominal cross sectional areas of 20mm^2 and 19.64mm^2, respectively. However, the gauge lengths are very different at 25mm and 10mm, respectively. Fabrication was either by direct moulding (designated DM) or moulding of oversize samples followed by machining to size (designated MM) to give either a moulded sample surface as would occur *in vivo* or a machined surface as used in many fatigue studies. This resulted in four specimens types: RDM, RMM, CDM and CMM. The specimens were examined for porosity using transmission of a bright light, then soaked in 37°C saline for between 1 and 6 weeks prior to testing.

Using an MTS – 858 Mini Bionix®II testing machine, the specimens were subjected to fully reversed tension-compression cyclic loading (force-controlled fatigue), at a maximum stress (stress amplitude) of 12.5, 15.0, 20.0 or 30.0 MPa at a frequency of 2 Hz under the flow of saline at 37°C. The highest stress of 30 MPa was selected assuming that the specimens would not buckle at this stress. According to Euler buckling calculations, if entire length between the grips was at the gauge cross section, compression stress levels of at least 31 or 35 MPa are required to produce buckling for the rectangular and circular specimens, respectively, however, the presence of the sample shoulders lead to a substantially higher Euler buckling load. The number of cycles to failure were recorded, with run-out set at 5 million load cycles [7-9]. The specimens that were found after testing to have pores with a major diameter of 1mm or greater in the gauge section were excluded and replaced [22, 23].

2.3. Fatigue data analysis

In order to compare the various fatigue testing regimes at a range of *in vitro* stress amplitudes as they have been reported in the literature, S-N or Wöhler curves were used. For each specimen type at each stress amplitude, a minimum of five specimens were tested, with 8 samples tested at 20MPa. This sample size is close to that postulated by ASTM E739-91 [24] of a minimum of 6 specimens when performing S-N curves, but less than that required by ASTM2118-14.

However, in earlier S-N testing of bone cement, a range of different sample sizes per group have been used, for example, 1 to 3 specimens [19], 5 specimens [11] or 8 specimens [8]. All the S-N curves were plotted for the stress amplitudes of 12.5, 15, 20 and 30 MPa (independent controlled variable) against the logarithm to base 10 of the cycles to failure (dependent random variable) [8, 10, 12].

S-N curves with regression line were generated for each sample type to assist in predicting fatigue lives at lower stress amplitudes based on the assumption that the relationship between the stresses and number of cycles to failure is approximately linear [12]. The fatigue results were compared, using these curves, for different specimen configuration and fabrication methods and the effect of the variation in cement composition. The equations of the S-N lines involve identifying the regression coefficients (slopes) where the analysis of variance between these slopes can be valuable in predicting and comparing the fatigue lives at lower stress amplitudes.

2.4. Differential Scanning Calorimetry (DSC)

The aim of the DSC analysis was, firstly, to estimate the degree of polymerisation for each specimen group and, secondly, to find any significant variations between the specimen types. Specimens with the median fatigue lives of those tested at ±20 MPa were used for the analysis. After fatigue failure, each of these median fatigue life specimens was ground using a clean and rough hand file near the fracture surface to obtain "grated cement". An approximately 5mg sample was placed in an aluminium pan in the DSC chamber (DSA-Q100, TA Instruments) with an empty aluminium pan as reference.

The analysis involved three successive processes: (1) heating the sample from 25°C to 180°C, (2) cooling it to the initial start temperature of 25°C and (3) heating it for a second time to 180°C, all at 10 °C min^{-1}. The heat flow of the three processes was plotted against the temperature and the two heating processes (heat flow vs temperature) were compared. The difference between the first and second heating exotherms is due to any non-polymerised monomer, since any remaining monomer undergoes polymerisation during the first heating process, resulting in the release of polymerisation energy, which does not occur during the second, enabling the amount of non-reacted MMA monomer in the specimen to be calculated [25], using the specific heat of polymerisation of MMA of 576 J g^{-1} [26]. The results were compared and differences were analysed using Student's *t*-test.

3. RESULTS

3.1. *General comparison of S-N curves of various specimen types*

The S-N curves (Figure 1) show obvious differences between the fatigue behaviour of the two cements. For both bone cements, the effect of specimen shape in conjunction with surface preparation method is clear. Consistantly, the longest fatigue life was associated with the circular moulded (CMM) specimens at all stress amplitudes. Excluding this specimen type, the results appeared to be more dependent on the change in chemical composition where divergence in the trends of S-N curves was seen amongst the two cements. While the circular machined (CDM) specimens for SmartSet GHV, for example, provided the shortest fatigue lives, this was not the case for CMW1 cement where the rectangular machined (RMM) specimen type had the lowest fatigue life.

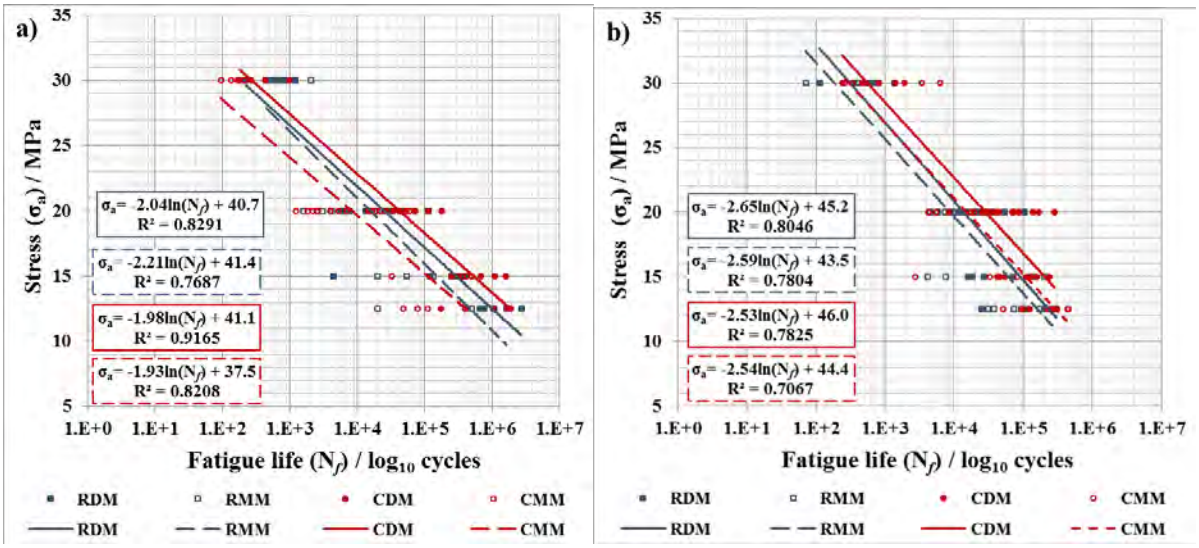

Figure 1 General comparison of S-N curves generated from testing at four fully reversed tension-compression stress amplitudes, comparing fatigue behaviour of four specimen types of a) SmartSet GHV (blue) and b) CMW1 bone cements (red).

Thereafter the fatigue results were largely controlled by the specimen shape and surface finish. These trends can be assessed and compared depending on the difference in the slopes (regression coefficients) of the curves. For SmartSet GHV specimens (Figure 1a), the gradient of the RMM specimens (a slope of -2.21) provided a different trend, while for the other sample shapes the regression lines were approximately parallel (gradients -1.83 to -2.04), but with different intercepts. At 20 MPa the differences between the four sample shapes leads to a maximum factor of 4.90 between the highest and lowest fatigue lives for CDM and CMM, respectively. For the CMW1 (Figure 1b), gradients (range -2.53 to -2.65) are higher than for SmartSet GHV with, at 20MPa stress amplitude, a factor of 3.33 difference between the fatigue lives for CDM and RMM samples. As testing was performed at higher stress levels than the typical stress levels applied *in vivo*, the decrease in the slope of an S-N curve may be used to indicate which specimen type might provide the highest fatigue results at the *in vivo* stress levels.

3.2. *Comparison of S-N curves of the same specimen type of different cements*

S-N curves comparing the two bone cements with the same specimen preparation method are shown in Figure 2. Changes in stress amplitude had different effects on the behaviour of S-N curves for the same specimen type. For all specimen types, a general trend of longer fatigue lives was found at the higher stress amplitudes (30 & 20 MPa), particularly for the circular shape, for the CMW1 specimens compared to the SmartSet GHV ones. However, at the lower amplitudes (±15 & ±12.5 MPa), nearer the *in vivo* stress levels, the fatigue trends were reversed, with SmartSet GHV showing longer fatigue lives. In Figures 2 a, b and c, the behaviour is similar with limited differences at 30MPa, but the differences between the two cements becoming more obvious at 15 and 12.5MPa. However for CMM samples (Figure 2d) the differences are apparent at 30MPa, but not at 15 and 12.5MPa.

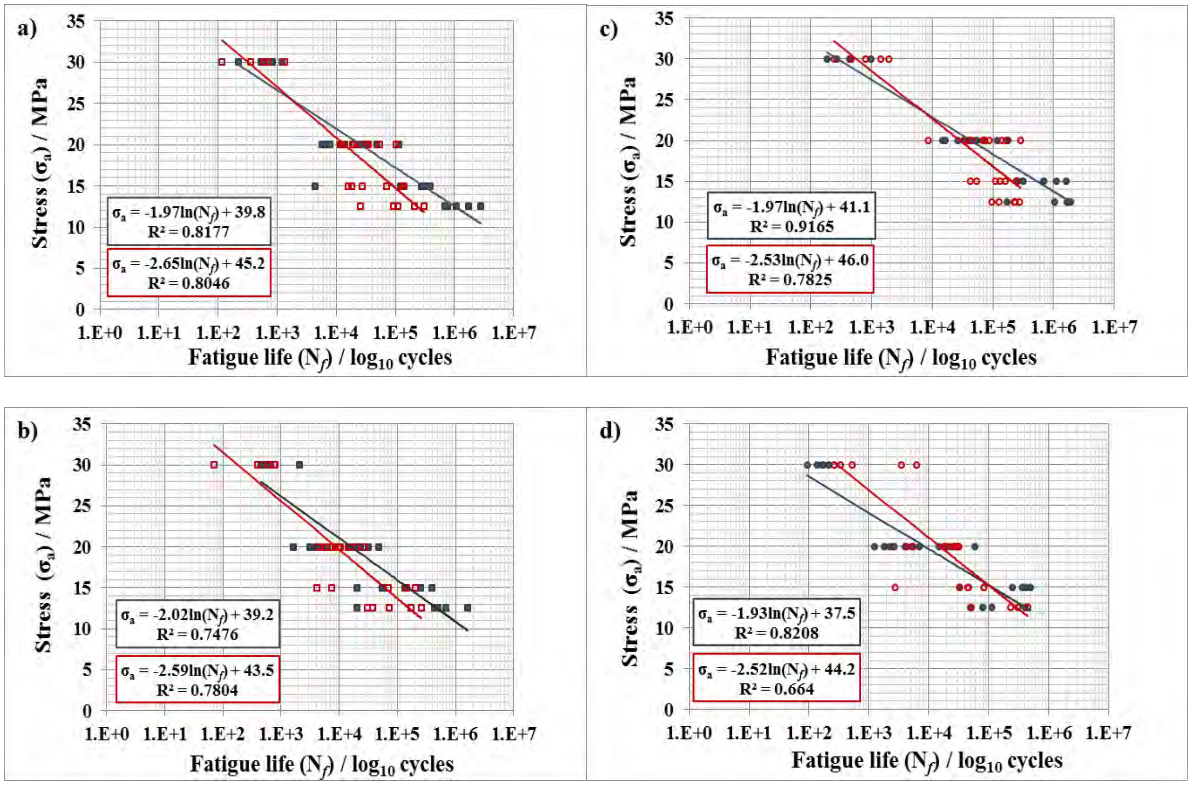

Figure 2 Comparison of S-N curves of SmartSet cement (blue) and CMW1 cement (red) using specimen types of a) RDM, b) RMM, c) CDM and d) CMM.

If all the results of the same cement are combined, regardless of specimen type, the stress-life relationship is given in Equations 1 and 2, for SmartSet GHV and CWM1 respectively. Although, for each cement, there are differences produced by the specimen shape and production method, the trend in the results is unaffected by the specimen specification (the S-N curves for the same cement are nearly parallel).

$$\sigma_a = -1.91 \ln(N_f) + 38.87 \qquad (1)$$

$$\sigma_a = -2.47 \ln(N_f) + 43.70 \qquad (2)$$

3.3. *DSC analysis*

The analysis of the DSC results indicated minor differences between all specimen types. As can be seen from the graphs (Figure 3), for all specimens, the initial heating of the cement to 180˚C, cooling it to room temperature and repeating the heating process provided only small differences between the two heating processes. Although this indicated that the majority of the MMA liquid reacted, the differences between the two heating processes showed that polymerisation was not complete, even after a minimum of one week at 37˚C, reflecting the presence of small amounts of residual non reacted monomer. Table 1 compares the estimated degree of polymerisation for the different samples, no obvious trends are seen.

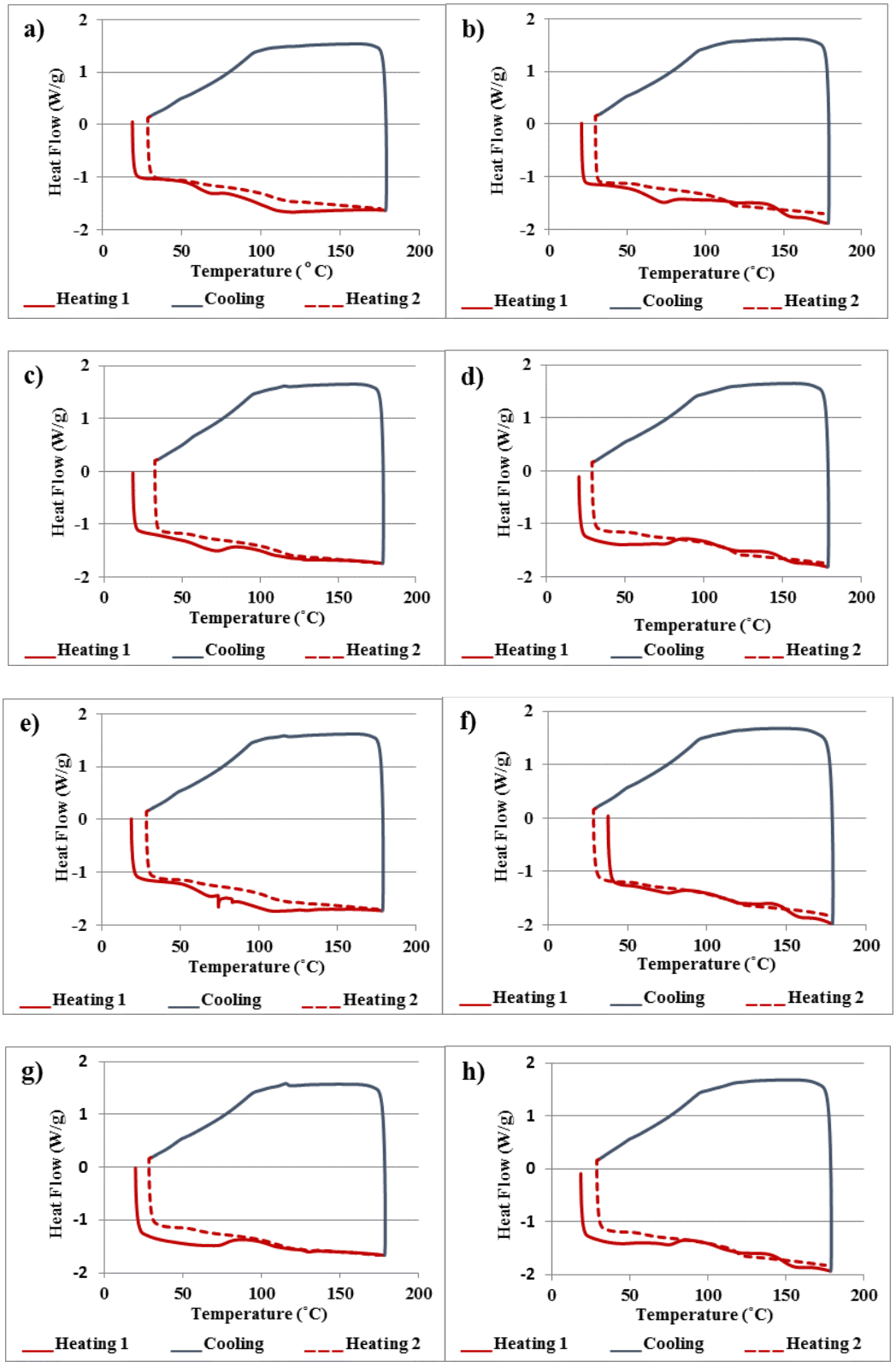

Figure 3 Comparison of the DSC analysis of different specimen types: RDM (a & b), RMM (c & d), CDM (e & f) and CMM (g & h) where a, c, e and g are for SmartSet GHV and b, d, f and h for CMW1

Table 1 Comparison of the estimated degree of polymerisation for all specimen types

Specimen type	Degree of polymerisation (%)	
	SmartSet GHV	CMW1
RDM	90	86
RMM	92.5	93
CDM	82	91
CMM	84.5	92

4. DISCUSSION

4.1 *Effects of specimen cross-sectional shape and size*

The analysis of fatigue results using S-N curves has shown that specimen shape and surface production method (specimen type) can significantly alter the measured fatigue life of bone cement, supporting the trends of our previous findings using tension-tension and tension-compression both at a single stress amplitude and using the Weibull functions for data analysis [7, 9]. The effect of specimen shape on fatigue behaviour can be influenced by the material, thus two different cement formulations have been investigated. In a number of early studies the use of particular specimen profiles, similar to those applied in testing of metals, led to "unrepresentative modes of failure" [27] and thus the development of the current standards [17, 18]. The concerns over the influence of specimen shape has also been reported for fatigue testing of bone cement as to which specimen shape (rectangular or circular cross sectioned) is more appropriate and representative of the *in vivo* conditions. The propensity of the circular specimens to generally provide greater fatigue strength, particularly when moulded, can be attributed to several factors. The most obvious reason is that the rectangular specimen, as we reported in detail previously [7], has larger gauge section surface area (450mm^2) and length (25mm) compared to the circular cross-sectional specimens (157mm^2 and 10mm, respectively) although the cross-sectional areas are similar. The importance of this factor is emphasised since it has been demonstrated practically that many polymers, similar to other materials, show early fatigue failure due to the initiation of cracks on the outer surface [28]. This phenomenon appears to apply to these specimens, but with the influence of this factor being controlled by specimen shape, along with production method and cement composition.

Another reason that has been observed to contribute to recording shorter fatigue lives with the rectangular shape is the corners along the section length of the test specimens. Corners, as also shown in a previous study [29] for acrylic glass specimens, thus pre-polymerised PMMA, increased the stress concentration in the rectangular specimens, which became more important if pores or defects existed near the corners, providing the most obvious fatigue crack origins as these specimens showed the shortest fatigue lives in their groups. The existence of similar defects near the circumference in circular specimens did not lead to reductions in the fatigue lives. In support of this, it has been stated that the argument about the role of porosity is "an artefact of the specimen design, rather than a change in the properties of the material" [30].

The effect of specimen shape on the degree of polymerisation needs to be considered, higher polymerisation increases the tensile strength of polymers [31]. For bone cement, any residual monomer amount "acts as a plasticizer" that results in lower yield stress values, but probably increases the material's toughness [32]. The greater fatigue performance for the circular cross sectional specimens compared to the rectangular has been previously attributed solely to the higher degree of polymerisation [5], but this is not seen in this study. Some difference in the degree of polymerisation has been seen when comparing the same specimen shape of both cements (moulded or machined) against the other specimen shape (Table 1), but the variations in the degree of polymerisation were statistically non significant (p-value of 0.17) and did not show any systematic effect.

4.2 *Surface preparation effects*

Many studies have examined the effect of the procedures included in the moulding process, but not the moulding itself, on the final quality of produced specimens (e.g. [33-36]). Pennati *et al.* [37] considered the direct influence of changing the moulding protocol on fatigue properties of a single bone cement, with no machining included and using rectangular specimens tested in zero-to-tension in air at room temperature, and concluded that fatigue strength results are greatly affected by the specimen moulding technique, principally the mixing and pressurisation processes. It has been reported that the presence of a "skin" layer on a moulded rather than machined notch in acetal copolymer specimens increases the fatigue properties by resisting crack initiation [38]. For the bone cements in the current study, however, the formation of an outer protective layer has not been obvious. In some cases, at the fracture, specimens were observed to have surface defects on their outer layers, leading to early fatigue failure of these specimens, which is potentially one of the reasons for wider variations in the fatigue lives of the moulded specimens.

In addition, it is well known that air bubbles can be incorporated during the mixing stage, which are reduced by using vacuum mixing systems, but some pores still remain. There is also a chance for the formation of air bubbles due to evaporation of the monomer during the early and higher temperature stages of polymerisation [39, 40] which can transfer towards the surface or stay within the specimens, providing both surface- and volume-distributed pores. As reported by Bhambri and Gilbertson [41] "in some cases the crack initiated from internal defects in the presence of near-surface defects at the fracture plane" and this behaviour was apparent in the current study. The fracture surfaces of many moulded specimens, however, have indicated that the relevance of the pores formed within the specimen depends on the pore size, shape and by the position of the pores within the fracture surface such that, for both specimen shapes, the closer the pore is to the outer surface the greater is its effect, despite being in a uniform stress field.

In terms of the effect of machining on surface roughness and fatigue life, it has been observed that, in general, fatigue life declined significantly for the majority of the machined specimens of both cross sections compared to the moulded specimens. This effect can be attributed to the interaction of several causes. Machining of the cast bone cement blanks leads to the removal of the outer "crack-resisting" layer provided by moulding; this observation has been reported earlier [6]. This change in the surface finish is more likely to contribute to recording shorter fatigue lives since the internal pores and defects become emergent on the outer surface and these pores and defects have increased crack initiation potential.

In addition to the decrease in surface quality due to machining, other reactions might exist leading to changes even in the properties of the material's original structure. Polymers in general have a chance to form free radicals during machining leading to breakage of bonds [42]. It has also been reported the shear forces generated during machining can increase the chance of breaking covalent bonds [43]. Interpreting the results obtained in this study according to these concepts will certainly mean that the change in the surface properties due to machining of bone cement led to more potential crack initiation sites enhancing the occurrence of earlier fatigue failure.

The type and direction of machining needs to be considered, particularly when machining different specimen shapes. During machining of the rectangular specimens, the cutting tool moves longitudinally along the specimen machining the four specimen sides sequentially and removing the material parallel with the future loading direction. When machining the circular cross sections, however, the specimen is rotated while the specimen outer surface is removed circularly. After machining, both types of specimens show fine machining lines (visible under an optical microscope) parallel to the load direction for the rectangular specimens and perpendicular to the load direction for the circular specimens. Nevertheless, the effect of perpendicular machining direction in relative to the testing axis for the circular specimens has been found to be influenced by the change in cement composition. The circular machined SmartSet GHV specimens appear to be more sensitive to the machining process than their CMW1 counterparts. There are differences in the response to fatigue of these two bone cements, as SmartSet GHV fatigues the energy absorbed per load cycle increases and the sample modulus reduces early in the process while

CMW1 is almost unaffected until very soon before actual failure [7]. These effects are increased and start earlier in the machined and particularly the circular machined (CMM) compared to the moulded samples [7]. Whereas for both shapes in CMW1 and rectangular samples of SmartSet GHV the reduction in the fatigue lives by machining the samples is about a factor of approximately 2.5, for the circular machined this factor is doubled.

4.3 *Effects of cement powder inclusions*

While the fatigue results have shown variations due to using different specimen types, the cement composition has meanwhile appeared to influence these variations. When testing at different stress amplitudes, the S-N analysis (Figure 1) has clearly shown that, in general, the moulded specimen, particularly the circular, provide longer fatigue lives. It has been shown in many studies that modifying the chemical compositions or inclusions can variously alter the fatigue properties. Some workers believed that the chemical composition plays a role even greater than porosity stating that "the dominant determinant of the fatigue life of different commercially available bone cements is their basic composition not their porosity" [44]. The findings of the current study have also demonstrated that variations in chemical inclusions can alter fatigue performance; however, these variations are altered by the stress regime (specimen type and stress amplitude). It is necessary, therefore, to consider some possible reasons for changes in the fatigue life of these two cements.

As discussed earlier [7], the SmartSet GHV specimens contain 9.76wt% zirconium dioxide and 2.87wt% gentamicin whereas CMW1 contains 6.18wt% barium sulphate and no antibiotic, leading to estimated volume contents of 2.20 vol% zirconium dioxide and 1.70 vol% of barium sulphate in the SmartSet GHV and CMW1 specimens respectively. This factor is important to emphasise since it can be vital in governing the fatigue life of bone cement. For materials in general, it has been reported that "the presence of inclusions by an order of magnitude larger than the machined surface roughness, generally overrides the effect of surface topography" [45].

Figure 4 compares the fracture surfaces of both cements at a range of magnifications. SmartSet GHV fracture surfaces, in addition to including more additives, indicate that the ZrO_2 opacifier particles are agglomerates of spherical subparticles compared to the individual $BaSO_4$ particles within the CMW1. These ZrO_2 opacifier agglomerates are typically 10-20μm across compared to the less than 5μm $BaSO_4$ particles This difference in opacifier content and size, along with the difference in the basic polymer structure of the cements, provides a possible cause for rougher fracture surfaces for SmartSet GHV compared to CMW1. One factor that might be worth considering when it comes to the random distribution of the opacifier particles, particularly for SmartSet GHV, is the effect of the mixing method used in this study. Whilst vacuum mixing is capable of reducing porosity to a large extent, it is not aimed at providing even filler distribution.

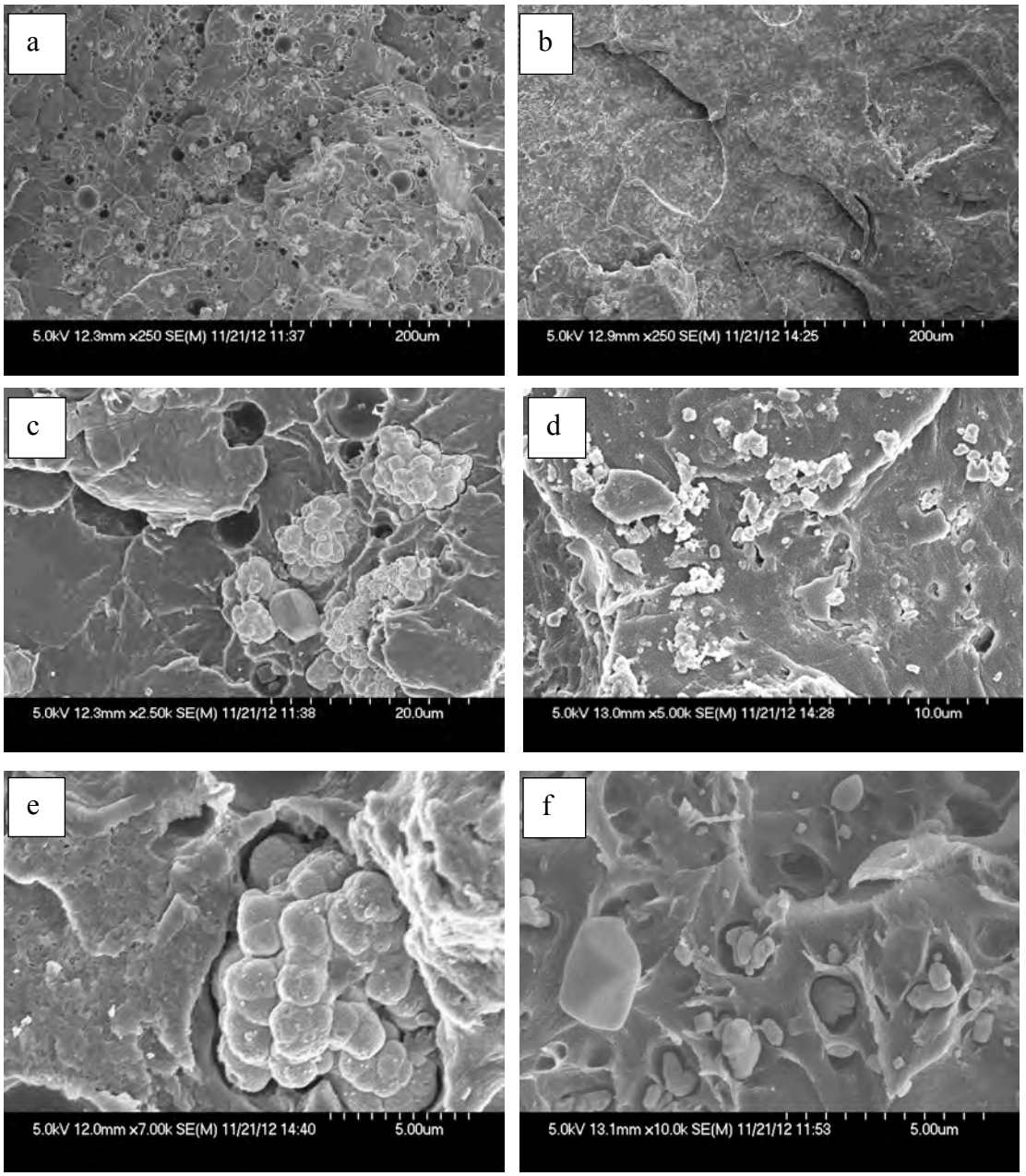

Figure 4 Micrographs of fracture surfaces compare the likely spread and accumulation of the two different opacifier particles in (a, c, e) SmartSet GHV and (b, d, f) CMW1, at different microscale magnification levels (a & b marker bars = 200µm, c marker bars = 20µm, d marker bars = 10µm and e & f marker bars = 5µm).

In moulded samples, the inclusions provide less detrimental effects on fatigue life for both cements used in this study. Machining the surface leads to cutting through opacifier accumulations near the surface potentially producing more crack initiation sites. The difference in powder chemical composition has been shown in this study to lead to dissimilar fatigue lives for both of the machined specimen shapes reflecting perhaps the difference between the filler response in both cements to the machining impact and direction since the rectangular machined specimens of SmartSet GHV provided longer fatigue lives compared to the CMW1 counterparts and vice versa for circular machined specimens.

4.4 Effect of Stress Level

The difference in fatigue behaviour at the high and low stress amplitudes for the two cements can be attributed also to other causes including the difference in molecular weight, thermal properties and creep behaviour. These factors are important since they can govern the crack initiation and propagation under fatigue loading. Overall, testing should be performed considering the influence of specimen type and, more importantly, the effect of

the stress amplitude to avoid overstressing the specimen and, therefore, to prevent fatigue failure due to the thermal effects. As can be seen from Figure 2, at 30MPa for all sample shapes CMW1 has a longer fatigue life, but at 20MPa and lower stress levels SmartSet GHV has the longer fatigue life. If the linearity of the S-N curve, as assumed by authors such as Murphy and Prendergast [12] who examined a range of stress amplitudes between 13 and 25 MPa using zero-to-tension loading at 10 Hz, can continue to lower amplitudes than those examined in the current study (say down to 7 MPa that represents the average stress encountered *in vivo*), then the *in vitro* fatigue life can be estimated at these amplitudes, which will be rather difficult to measure experimentally by direct testing due to being time consuming when using as low test frequency as 2-5 Hz and typically at 10MPa 5million load cycle runouts occur [8]. It is to be considered also, the mode of stress (tension-compression or tension-only) as demonstrated earlier [9] is important in identifying the highest stress amplitudes that are appropriate to include in testing and establishing more accurate S-N curves to predict the fatigue life at the *in vivo* stress levels.

CONCLUSIONS

- For the same cement composition, the response of fatigue crack initiation and growth appears to be controlled by the specimen configuration and fabrication method used. In general, moulded specimens, particularly with circular cross sections, tend to provide significantly longer fatigue lives than the machined samples at all stress amplitudes. Thus supporting the requirements of the current standards to have moulded surfaces.
- The same specimen configuration and fabrication of different cement compositions can possibly provide unlike or contradictory fatigue behaviour at different stress amplitudes. Considering the *in vivo* stress levels, high *in vitro* stresses can likely lead to misleading indications for the clinical fatigue performance of particular cements compared to others.
- Overall, there is a stress amplitude above which the fatigue behaviour is not representative to the *in vivo* conditions. Specimen type does not seem to largely affect this aspect and in this fully reversed fatigue study is less than 30MPa, agreeing with the stress levels given in the standards.

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