Introduction

There is now worldwide interest in using fine ceramics and ceramic composites as key load-bearing components for gas turbines, aerospace and other advanced engineering applications. Their cost-efficient and yet safe usage will rely on a combination of computer-aided engineering design procedures and a database of properties at temperatures of commercial interest ($>1200^\circ C$) that will be extensive by historic standards for these materials. Standardisation of measurement and test procedures for procuring accurate values of material properties will be of great importance because their relative intolerance to stress concentrations leads to data-scatter due to variations in specimen geometry, surface finish, internal defects and loading misalignment. Such standards in the field are only now being developed and at present there is little worldwide co-operation in this area.

For these reasons, the High Temperature Mechanical Testing Committee organised a symposium on *Mechanical Testing of Engineering Ceramics at High Temperatures* in April 1988. The meeting was held, in collaboration with the National Physical Laboratory and the Institute of Ceramics, at the Excelsior Hotel, Heathrow, London, UK. The primary aims of the High Temperature Mechanical Testing Committee, whose secretariat is at the National Physical Laboratory (NPL), are to promote discussion, development and, where appropriate, standardisation of testing techniques. This meeting was the fourth in a series devoted to pursuing these aims: the first was held at the NPL in 1981 and the proceedings were published as *Measurement of High Temperature Mechanical Properties of Materials*, edited by M. S. Loveday, M. F. Day and B. F. Dyson (HMSO, London, 1982); the second was held at Preston in 1983 under the auspices of Springfields Nuclear Power Development Laboratories, and the proceedings published as *Techniques for High Temperature Fatigue Testing*, edited by G. Sumner and V. B. Livesey (Elsevier Applied Science, London, 1985); the third was held at the Central Electricity Research Laboratories, Leatherhead, in 1985 under the auspices of the Central Electricity Generating Board and ERA Technology Ltd; the proceedings were published as *Techniques for Multiaxial Creep Testing*, edited by D. J. Gooch and I. M. How (Elsevier Applied Science, 1986). The present volume consists of the edited proceedings of the 1988 meeting: the majority of the papers were by invitation but a number of shorter papers, presented at the conference as posters, are also included.

The book is divided into three sections: the first, containing three invited chapters, reviews the industrial requirements for mechanical property data, the current test methods and the need for standards; the second section of four invited chapters contains reviews on machine design requirements, strain measurement for uniaxial testing and the stringent demands required of furnace design and temperature control; the third section of six invited and six contributed chapters provides the state-of-the-art as far as techniques for tensile testing, uniaxial tensile creep, cyclic fatigue, fracture toughness and sliding friction and wear are concerned.

In Paper 1, Butler places great emphasis on the different testing requirements for 'alloy' development and design: although flexure is an adequate test procedure for 'alloy' development, its statically-indeterminate stress field does not allow quantitative interpretation of results when anelastic and inelastic (creep and cyclic fatigue) behaviour are being assessed.

Loveday and Morrell make the important point that harmonisation with ISO Standards should be encouraged since, where these exist, they are being adopted as drafts for the new European Standards: the latter will supersede the equivalent national Standards of the member nations of the European Community. After presentation of their paper at the conference, a lively discussion concluded that there may be a general consensus for the US Mil Standard 1942 to form the basis of the ISO Standard for bend testing. It is also clear from their paper that accurate measurement of testpiece temperature above 1200°C is a major unresolved problem which has to be overcome if accurate design data are to be generated.

Grathwohl's excellent review of current testing methods contains a well argued case on the advantages and disadvantages of the flexure test, which should serve well as a future reference.

In Part II, Amaral and Pollock strongly point out that data-scatter in ceramics can be large and the results questionable, simply because inadequate attention has been paid to the quality of the test procedures used: unlike metals, ceramics are very unforgiving towards imperfect test methods. This is particularly relevant to tension and/or compression testing at these very high temperatures where attention to detail is paramount. As an example, they present the advantages and disadvantages of 'hot' versus 'cold' grips,† coming down in favour of the latter provided it is recognised that great care needs to be taken in furnace design to achieve an acceptable temperature gradient on the specimen (see also Loveday & Morrell).

Liu *et al.* consider strain measurements for three modes of tensile testing; tensile fast fracture, dynamic cyclic fatigue and creep. A strong case is made for laser-based, non-contact optical strain extensometry for high-temperature applications. Consideration of methods for heating testpieces and achieving accurate control of test temperature are a crucial aspect and are dealt with in papers by Buddery and by Liu.

In Part III, Ohji demonstrates that with care and suitable attention to testpiece gripping detail, tensile tests on ceramics at temperatures up to 1300°C can be performed with acceptable accuracy. In an elegant series of experiments, he quantifies the importance of removing machining defects if the 'intrinsic' strength is to be measured.

Carroll and Wiederhorn describe an interesting device for measuring uniaxial creep strain, using an optical telescope which allows a resolution of 2 μm at 1300°C. Kandil and Dyson focus on the importance of accuracy in the alignment of the uniaxial load train and also temperature control when procuring creep data for design. In the discussion following their paper, it was pointed out that the errors involved in using an indirect measure of strain are small compared to the errors found in the majority of systems due to misalignment and poor temperature control and measurement.

The paper by Soma *et al.* demonstrates that NGK Insulators are ahead of the field when it comes to elevated temperature fatigue: testing at temperatures up to 1500°C are routinely performed under tension, compression and torsion as well as combined tension/torsion. Careful design of gripping systems is the key to their success.

Rief and Kromp demonstrate that K_{IC} as a 'materials constant' can be measured in ceramics by flexure. Sufficient understanding of the factors causing scatter now exists to be confident that there will soon be a standardised K_{IC}-testing procedure.

In contrast to the situation described by Kromp with monolithic ceramics, Davidge and Davies point out that high-toughness ceramic-matrix composites (CMC) do not obey the basic concepts of fracture

† Editors' Note: 'Cold' is a relative term; for example, the face of a 'cold' grip may be at *c.* 1000°C when testing at 1500°C. The term 'warm' is now starting to be used.

mechanics. The field of CMC is still at a relatively early stage of development and more understanding of behaviour will be necessary before standardised test methods merge to provide consistent and, in some cases, relevant design data.

It remains to thank the Editorial Panel for their valuable and prompt assistance in reviewing the manuscripts and the many people who helped in organising the symposium: the efforts of Mr B. Larcombe is particularly acknowledged. To the authors, we extend especial thanks, for without them the subject could not have been documented.

B. F. Dyson

R. D. Lohr

R. Morrell