MATERIALS FORUM VOLUME 30 - 2006
Edited by R. Wuhrer and M. Cortie

ADVANCED HIGH TEMPERATURE TESTING OF FERRITIC PRESSURE VESSEL STEEL

S. R. Humphries[1], M. D. Callaghan[2], B. A. Latella[1], K. U. Snowden[1] and W. Yeung[2]

[1]Institute of Materials and Engineering Science, Australian Nuclear Science and Technology Organisation, Private Mail Bag 1, Menai NSW 2234, Australia.
[2]Department of Chemistry, Materials and Forensic Science, University of Technology, Sydney, PO Box 123, Broadway NSW 2007, Australia.

ABSTRACT

This work describes three test methods employed to assess the condition of components in high temperature power generation plant. These are stress relaxation on miniature samples from service aged material, low cycle fatigue testing by strain control and Young's Modulus determination by an impulse excitation technique. Data are presented from tests on 2.25Cr-1Mo virgin and service-aged steel and the application of data to life assessment procedures is discussed.

1. INTRODUCTION

Ferritic steels are used extensively in the manufacture of high-temperature pressure equipment for fossil-fueled power generation plant. This type of plant operates under conditions of stress and temperature which may cause some components to undergo creep. The onset and subsequent accumulation of creep damage will eventually lead to cracking and therefore redundancy or failure of the component.

During the design life of a typical power generation unit, staged assessments are conducted to determine the metallurgical condition of the plant. These assessments require the use of non-destructive methods to detect defects and surface replication techniques to assess microstructural degradation. However, if a component is well into its design life it may be necessary to remove samples for the purpose of creep testing. Accelerated temperature creep testing on miniature samples from in-service components is a well established technique used to obtain an estimate of remaining service life. However, creep testing does not quantify other damage mechanisms which can also influence the service life of components.

Pressure vessels for power generation plant are complex arrangements of steam pipe-work and large steam collection pipes known as headers. A typical header may have dimensions of 500 mm outside diameter (OD) by 100 mm wall thickness and could be up to 20 metres long. Most large units operate at temperatures of 540-560°C and steam pressure of 16 MPa. During steady state operation the hoop-stress within the headers is approximately 35 MPa, however, during periods of heat-up and cool-down stresses in some locations may be much higher. Load and thermal transients encountered during these periods lead to high multi-axial stresses acting at stress concentration sites such as welds and fillets or at branch intersections where the component geometry changes.

Load cycling of power plant is now commonly employed to meet peak supply demands, indicating that critical components are subjected to higher stresses and temperatures for a greater life fraction than would be experienced under base load conditions.[1] Strain accumulation and subsequent life consumption is therefore not governed solely by creep but rather the interaction of creep, stress-relaxation and fatigue.

Tests designed to determine tensile, stress relaxation and fatigue properties of metallic materials are well documented in published literature, apart from information on high temperature fatigue which is limited. Standard test methods however are restricted to full-size test samples, which, in the case of aging in-service equipment, are impractical to use as the integrity of the component will be compromised by removal of the sample material. Actual material data from in-service components is crucial, hence the need for miniature samples and development of test methods which give good correlation with standard test size samples.

In this work three test methods are summarized, stress relaxation on miniature samples, low cycle fatigue testing by strain control and Young's Modulus determination by an impulse excitation technique. These testing techniques, when used in conjunction with established methods, can provide valuable material data essential for remaining life assessment of high temperature components.

2. STRESS RELAXATION TESTING

Stress relaxation (SR) is described as 'the decrease in stress with time caused by the conversion of elastic strain to inelastic strain.' Strain controlled SR tests are performed, in a tensile mode, by loading the sample to achieve a predetermined strain and then monitoring the reduction in stress as the constraint is maintained. ASTM E328-86[2] and BS-EN-1:2003[3] both describe methods of SR testing which employ conventional tensile test samples, albeit, with increased gauge lengths to facilitate precise strain measurement and control. A parallel gauge length of 100 mm is common for SR samples. Obviously, samples of this size are impossible to extract from in-service components for the reasons already mentioned, therefore an alternative SR testing system was developed which employed samples of the size used in miniature creep testing.

2.1 Test System

The SR testing machine is of the sliding weight design which provides a stress range of 50-200 MPa to a 2 mm diameter sample. Load is measured by a strain gauge based 0-2 kN load cell with a resolution of 2 N. The sample and extensometry is contained within a vacuum chamber and sample temperature is measured by two Pt, Pt-13Rh thermocouples. Temperature control is crucial to the successful operation of the system as thermal expansion and contraction effects need to be kept at an absolute minimum.

The parallel gauge length of a miniature sample is 10 mm, consequently, 0.15% strain (the initial strain required in a typical SR test) equates to a total extension of 15µm. Extensometry that is suitable for strain measurement and control loop feedback must be capable of providing a stable, noise free output, resolvable to 1µm, coupled to a load control system that can maintain a constant strain on the sample to 0.01% or better. Although these control parameters are still outside the tolerance stated in ASTM E328-86[1] for standard size samples (0.0025%), better strain control on miniature samples was considered unattainable. However, during actual SR tests fine tuning of the strain control system enabled control limits of 0.005% to be achieved (see Fig 1). The extensometry specifically developed for this system achieved excellent control by utilizing a lever arm to magnify changes in strain occurring at the sample gauge length. Only minor alterations are required to miniature creep samples to accommodate the extensometry clamps.

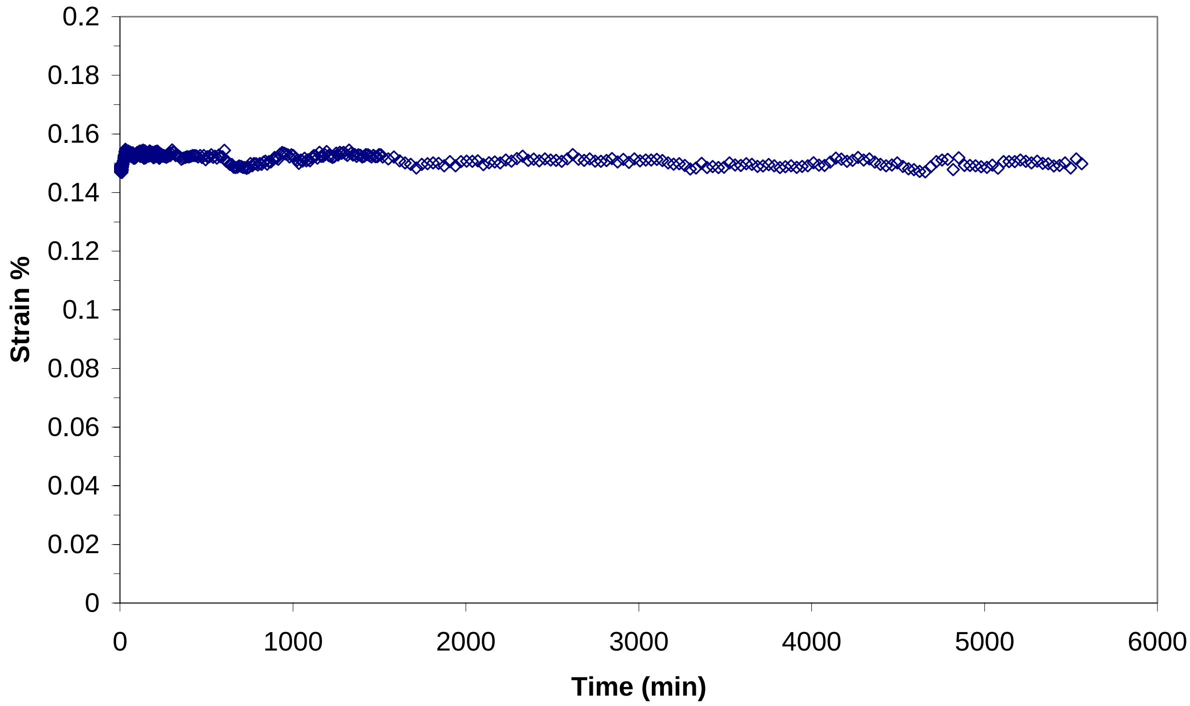

Figure 1. Typical strain control achieved during SR tests.

2.2 Materials and Testing

Tests have been conducted on samples of 2.25Cr-1Mo steel, which is used extensively in high temperature pressure equipment. Both service-aged and virgin material were tested.

Data obtained from SR testing can be applied to different equations eg Feltham[4] and Tanaka and Ohba[5] to describe the influence of stress relaxation on the behaviour of high temperature steels[6]. The assessment procedure known as R5[7], which is widely accepted as the most comprehensive guide to conducting life assessments of high temperature plant, states that 'the most appropriate form of the equation will depend on the material under consideration, the extent of the data available and the information available from stress analysis'. Lack of SR data, particularly for service aged material has been a major driving force behind the development of the test system described here.

Figure 2 depicts four out of a total of ten stress relaxation curves produced during a series of tests at 540°C. After testing, residual strain in the specimen measured 0.70% which was in good agreement with that of 0.64% calculated.

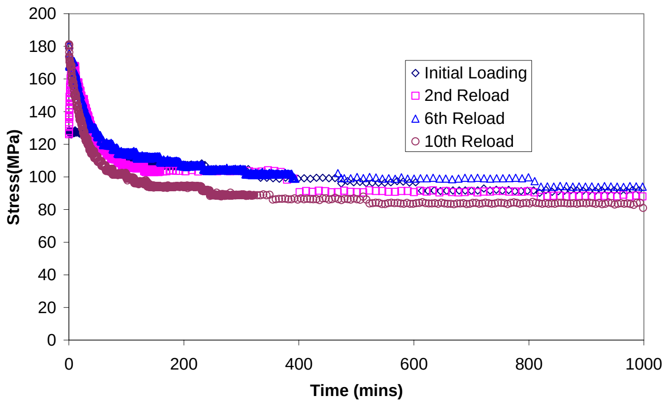

Figure 2. Stress relaxation curves obtained for 2.25Cr-1Mo steel at 540°C.

A feature of the equipment is that it enables a combination of stress relaxation and creep testing to be performed on the same sample. Consequently, the reduction in creep life of components due to increased cyclic loading can be investigated. The sample tested above was subsequently creep tested at 140 MPa and 540°C (see Fig 3). Rupture occurred after 640 hours, which is 390 hours less than the same material creep tested without prior SR testing.

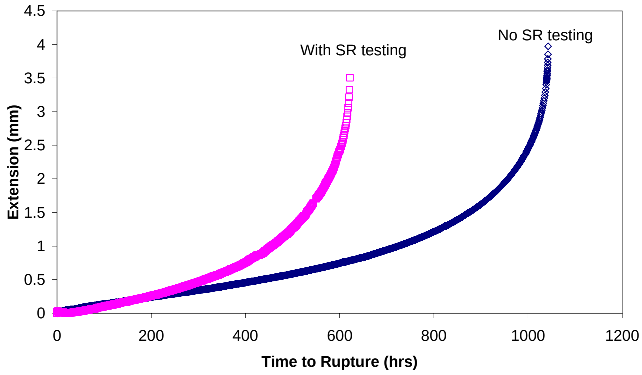

Figure 3. Creep curves for virgin and SR tested 2.25Cr-1Mo steel at 540°C and 140 MPa.

3. LOW CYCLE FATIGUE

High temperature low cycle fatigue (LCF) testing is conducted under strain control. Strain-controlled testing requires extremely accurate measurement of the strain in the specimen by means of extensometry. Conventional high temperature extensometry generally utilises quartz rods which attach to the specimen and transmit displacement to a transducer outside the furnace. This type of extensometry suffers disadvantages, such as contact effects on specimen fatigue endurance as it requires indents to be formed on the specimen gauge length.

In addition, a basic requirement in closed loop strain-controlled fatigue testing is for the extensometry to maintain its rigid mounting, on the specimen, for extended periods under cycling conditions. Complete rigidity can be difficult to achieve particularly if the extensometry is mounted on the gauge length. Some improvement can be obtained by mounting the extensometry on the shoulder section of the sample, however, this can lead to significant inaccuracies in strain measurement and subsequent control.

The method described here utilized an improved shoulder mounting technique and capacitance transducer. Calibration curves were obtained from comparative tests with conventional extensometry mounted on the gauge length. The ultimate objective of the method is for incorporation into miniature specimen high temperature LCF testing.

3.1 Method

Fatigue specimens were designed in accordance with ASTM E606-92[8] and manufactured from virgin 2.25Cr-1Mo steel plate. Brackets holding a capacitance transducer (8 mm in diameter) and its target were located in a small keyway and tack welded to the shoulders of the sample.
An Instron high temperature extensometer incorporating a quartz rod assembly, was used to measure the strain in

the gauge length of the specimen. The extensometer gauge length was set to 12.5 mm by two indentation points on the specimen.

The fatigue specimen, with capacitance transducer and extensometer attached was placed within a 3-zone furnace mounted on an Instron servo-hydraulic testing machine. Tensile tests at 23°C and 540°C were conducted under position control using a crosshead speed of 0.5 mm/min. Displacements from both transducers were logged along with load and position of the Instron ram.

Correlations of strain and displacement at the shoulder and gauge length at room and high temperature were determined from calibration tests. This enabled strain measurement and control for high temperature fatigue testing.

3.2 Testing

The comparative results of load versus displacement at 540°C for the high temperature and capacitance extensometry, mounted on the gauge length and shoulders of the specimen respectively, are shown in figure 4. The 23°C test is not shown graphically, as the 540°C test is more pertinent to the practical aspect of the testing.

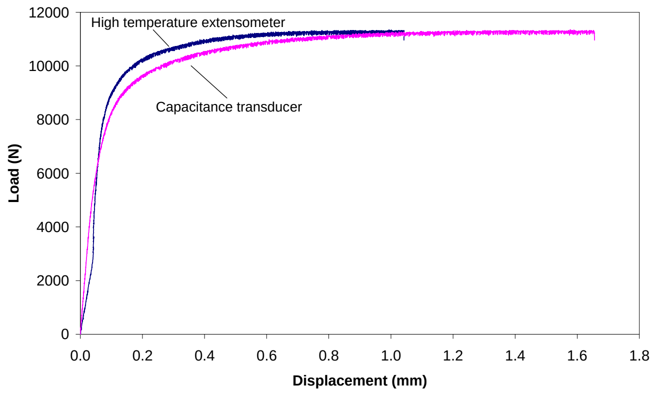

Figure 4. Load vs displacement curves at 540°C for 2.25Cr-1Mo steel from the high temperature extensometer and capacitance transducer.

Table 1. The equations and R^2 values determined from the calibration tests at 23°C and 540°C.

Parameter	23°C Test	540°C
Least squares fitted equation	Y=3.103x-0.05324	Y=4.931x-0.07672
R^2 value	0.9999	0.9992

From the load versus displacement results at 540°C (Fig. 4) for both devices, the displacement change at the shoulder-shoulder length is considerably larger. This is due to the greater volume of materials constrained within the shoulder-shoulder length compared to the gauge length. This was also the case at 23°C although higher loads were attained.

The calibration curves at 23°C and 540°C (Fig. 5) showed good linearity, evidenced by the correlation coefficient, R^2, values in table 1. The increased slope of the 540°C calibration curve is due to the smaller difference between gauge length and shoulder to shoulder extension. As a result of the least squares fits to these calibration curves accurate strain control during high temperature fatigue testing is possible (see Table 1).

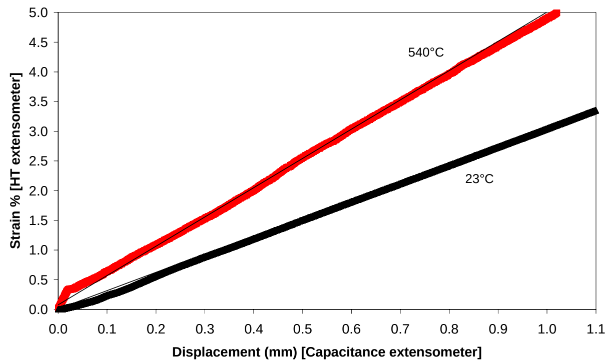

Figure 5. Calibration curve of strain % (Instron HT extensometry) vs displacement (capacitance transducer).

4. YOUNG'S MODULUS BY IMPULSE EXCITATION

The elastic properties of metals are important in the design of many high temperature components. Accordingly, elastic property data at ambient and high temperatures is fundamental for modelling purposes and damage assessment of these materials in service.

4.1 Method

In this work the elastic properties were ascertained for a service-aged 2.25Cr-1Mo steel component (280,000 h in operation, ≈ 32 years) taken from a power plant pressure vessel. Small specimens were wire cut from the component into rectangular bars of $l \approx 50$ mm $b \approx 5$ mm and $t \approx 3.5$ mm. Four samples were obtained from the component section with varying degrees of creep damage from near the outer face (location 1: heavily creep-damaged zone) to the inner face (location 4: minor creep damage). The length, width and thickness were measured using a vernier caliper and mass measured to four decimal places using an analytical balance.
The elastic properties of the four samples were measured at room temperature using the impulse excitation technique (IET) using a GrindoSonic Mk5 instrument (J.W. Lemmens, Belgium). It consists of an impulser, acoustic microphone and electronic system (signal amplifier, analyser and frequency read-out device). The sample is placed on soft foam supports at

nodal points (0.224*l*) and then tapped in the centre with the impulser (small steel ball glued to a flexible rod) to excite the fundamental flexural resonant frequency or at the edge of the sample on the nodal line to excite the fundamental torsional resonant frequency. Further details of the method can be found in the ASTM standard.[9]

The Young's modulus (E) and shear modulus (G) were determined from the flexural and torsional resonant frequencies, respectively and from the mass and dimensions of the sample.[9] With Poisson's ratio given by $\nu = (E/2G) - 1$.

4.2 Testing

Table 2 shows the room temperature elastic properties of the four samples along with the data from a virgin 2.25Cr-1Mo steel. It is clear from the data that there is a subtle drop in Young's modulus from the inner to outer face of the service-aged steel. The density of the steel also declines from location 4 to 1.

Table 2. Elastic properties of 2.25Cr-1Mo service-aged steel near the outer face (location 1) through the section (locations 2 and 3) to the inner face (location 4).

Location	Density (g/cm^3)	E (GPa)	G (GPa)	ν
1	7.75	210.3	82.5	0.275
2	7.77	210.7	82.6	0.275
3	7.77	211.2	82.8	0.276
4	7.78	212.4	83.0	0.280
Virgin material [ref]	7.80	212.4	82.4	0.288

Cavitation (porosity) resulting from in-service creep deformation is clear from the optical micrograph sections shown in Figure 6 and confirms the difference in the density of the steel from the four locations. This is manifested as a drop in the Young's modulus as shown in Table 2, and can described empirically by $E = E_O\exp(-bP)$ where E_O is the zero-porosity modulus, P is the porosity and b is a material constant.

In previous work the Young's modulus of virgin and aged material (96,000 h in operation, ≈ 11 years) as a function of temperature were shown to decrease steadily with increasing temperature[10]. Surface oxidation at elevated temperature was found have a minimal influence on the Young's modulus. The aged material displayed a slightly lower Young's modulus at temperature compared to the virgin steel, with both described by linear fits: (i) Virgin: $E = 216.2 - 0.0692T$ (R = 0.993); (ii) Aged: $E = 216.3 - 0.0766T$ (R = 0.990). Where E is in GPa, T is in °C and R is the correlation coefficient.

5. CONCLUSIONS

Three test methods designed to aid in the remaining life assessment of high temperature plant have been described:

- Stress relaxation tests on miniature samples have been conducted successfully in a strain controlled closed loop system
- In low cycle fatigue a capacitance transducer method has been developed to minimise inaccuracies associated with high temperature extensometry. Further development may lead to successful LCF testing on miniature samples.
- The IET has shown to be a reliable dynamic method of measuring elastic properties of small samples at ambient and high temperatures.

Access to data provided by these methods are important in remaining life assessment and structural design/modelling of high temperature plant.

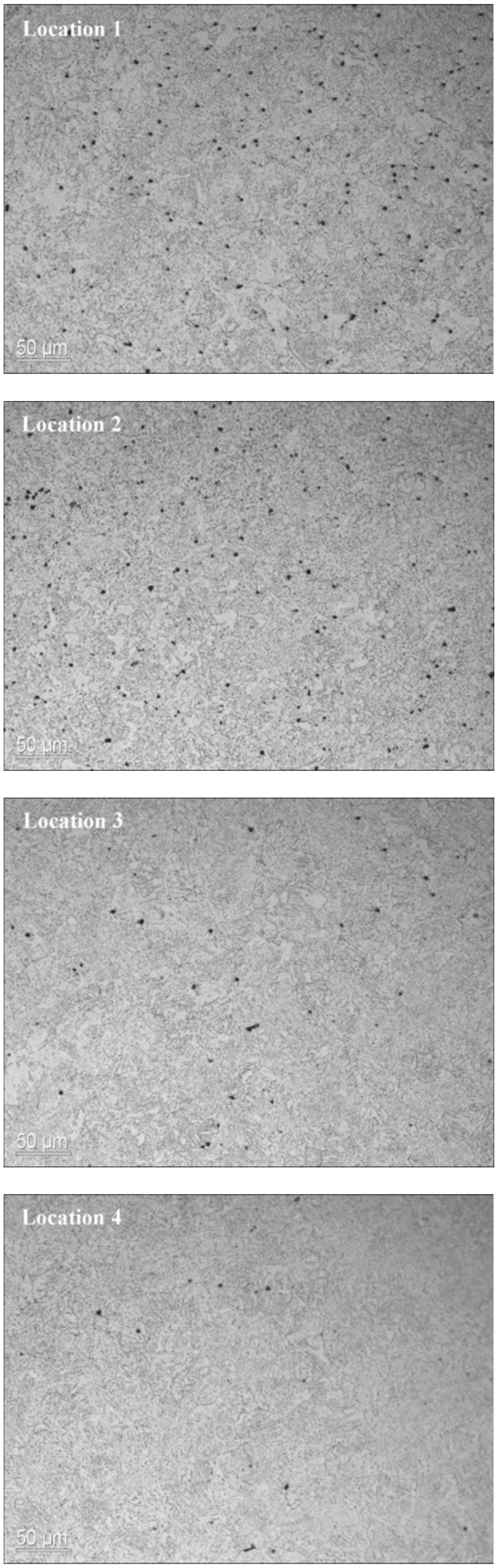

Figure 6. Optical micrographs showing decreasing degrees of cavitation (small black areas) from location 1-4 (refer to table 2 for details)

Acknowledgements

The authors would like to thank T. Nicholls and P. Guagliardo. MDC would like to acknowledge the Australian Institute of Nuclear Science and Engineering (AINSE) for resource contributions to this work.

References

1. A.B.L. Croker, S.R. Humphries, D.J. Mercer, C.J. Moss, W.M. Payten and K.U.Snowden. *Development of an On-Line System for Life Assessment of Elevated Temperature Pressure Plant,* Proc. International Conf on Operating Pressure Equipment, Brisbane, 9-11 April 1997, pp 281-284.

2. ASTM E328-86 (Re 1996) *Stress Relaxation Tests for Materials and Structures.* American Society for Testing and Materials, pp 1-12
3. BS-EN-1-2003. *Metallic Materials-Tensile Stress Relaxation Testing.* British Standard, 2003, pp 1-18.
4. P. Feltham, *J. Inst. Metals*, 1960-61, vol. 89, pp 210-214.
5. C. Tanaka and T. Ohba. *Trans. Nat. Res. Inst.*, 1984, vol. 26, pp 1-20.
6. K.U. Snowden, A.B.L. Croker, S.R. Humphries, W.M. Payten and R.F. Small. *Stress Relaxation and Requirements for Meeting the R5 Guidelines*, Conf Proc ICPVT 9, Sydney Aust, April 2000.
7. British Energy, BNFL and Serco, *Assessment Procedure for the High Temperature Response of Structures R5*, July 2003, Issue 3, rev 1.
8. ASTM E606-92, *Standard Test for Strain Controlled Fatigue Testing,* American Society for Testing and Materials. 1998, pp 1-15.
9. ASTM C1259-94: *Standard Test Method for Dynamic Young's Modulus, Shear Modulus and Poisson's Ratio for Advanced Ceramics by Impulse Excitation of Vibration*, American Society for Testing and Materials, 1994, pp 1-9.
10. B.A. Latella and S.R. Humphries. *Scripta Mat.*, 2004, vol 51(7), pp. 635-639.

MATERIALS FORUM

Materials and Testing

Volume 30, 2006 Edition

AUSTRALIA

The Institute of Materials Engineering Australasia Ltd
(Trading as Materials Australia)
A Technical Society of Engineers Australia
Suite 205, 21 Bedford St, North Melbourne, Victoria, 3051, Australia
email: imea@mateng.asn.au
website: www.mateng.asn.au

ABN 40 004 249 183

ISSN: 1447-6738
ISBN: 1 876855 258