MINIATURISED CREEP TESTING USING THE SMALL PUNCH (SP) TEST TECHNIQUE

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ABSTRACT

The condition assessment of power stations and petrochemical facilities is of paramount importance when ensuring safe and cost effective operation. Failures can have severe consequences in terms of repair costs, reduced revenue, loss of public confidence and most importantly, injury and fatalities. As many of the world's high-energy plants are nearing the end of their nominal 30-year design life, economic considerations are pressuring operators to extend their operating lives. This is possible by exploiting the fact that the initial designs were based on worst-case loading conditions and the application of generous safety margins. However, to enable a plant to continue operation, regular assessments have to be made of the residual life remaining in critical components. The assessment of the remaining life in components has been traditionally performed using uniaxial creep testing. Specimens used for this work are well defined in international standards and are generally in the order of 50-100mm in length and upwards of 10mm in diameter. However removing the relatively large amounts of material required for these specimens can lead to access, repair and cost issues. Hence the development of smaller specimens would reduce cost and make materials removal simpler.

This paper details the SP technique as it is employed at the University of Wales Swansea. The technique is fundamentally similar to those used by other European researchers, including Cracow University of Technology and IE JRC (Petten, The Netherlands). Specimens are disc shaped with a thickness of 0.5mm. Specimens are loaded with a hemispherical punch and the displacement is measured using high precision transducers. Results show that the technique displays good reproducibility with creep curves which exhibit primary, secondary and tertiary deformation in a manner with is analogous to standard uniaxial tests. The Monkman-Grant relationship and the values of power law creep exponent (n) and activation energy (Qc) obtained for disc tests are directly comparable to those from uniaxial tests. In addition, grain boundary cavitation damage was observed in the disc specimens. The success of this work shows that SP testing may provide a condition assessment tool worthy of consideration for worldwide standardisation and application.

1 INTRODUCTION

The condition assessment of ageing plant across the world is of primary importance for ensured continues safe and economic operations. Facilities such as power stations and petrochemical plants operate under conditions where materials properties can be degraded by both temperature and loading conditions and by aggressive chemical environments. Component failures under such conditions can be not only costly in monetary terms but also have potential for serious injury or loss of life for personnel. With plant now coming to the end of its 30-year design life, economic pressures are leading operators to utilise plant beyond that initial limit. This can be done safely due to the conservative nature of the initial design.

However, to enable a plant to continue to operate safely, regular assessments have to be made of the residual life remaining in critical components. This assessment is dependant on a number of factors:

i) Knowledge of the current damage condition of the plant.
ii) An appropriate failure criterion.
iii) An accurate prediction of the rate at which future damage will accumulate for a set of defined criteria.

The assessment of the amount of creep damage and thus remaining life in components has been traditionally assessed using standard uniaxial creep testing. Specimens used for this work are well defined in international standards and are generally in the order of 50-100mm in length and upwards of 10mm in diameter. Materials for these specimens has to be removed from locations on the plant where, either due to known high loading conditions or previous failure experiences, creep damage is suspected to be a problem. However, to manufacture standard sized creep specimens, relatively large amounts of material have to be cut from the plant using large equipment. This can lead to access and cost issues. Also, removal of large regions of material form plant which is due to be returned to service may require the resulting holes to be repaired using welding techniques. This can introduce further complications to the piping system in the form of a range of metallurgical and mechanical problems associated with welds.

Over the past decade, a range of miniature testing techniques have been developed with aim of overcoming the problems associated with the removal of large amount of materials from plant or cases where the amount of material available for testing is small. To this end, research programmes have been undertaken in the USA, Europe and Japan to using disc shaped specimens to evaluate the mechanical properties of a range of engineering materials [1,2,3]. In the Materials Research Centre at the University of Wales Swansea, a technique has been developed to creep test small disc specimens with a diameter of 9.5mm and a thickness of 0.5mm. With a number of international partners, including the Cracow University of Technology, Institute of Materials Science and Technology (Poland), European Commission Joint Research Centre (The Netherlands) and CESI (Italy), the technique has been further developed in the form of a European round-robin programme to assess the potential of standardising the technique for future application as an industry-approved damage assessment technique.

This paper details the SP technique as it is used at the University of Wales Swansea. The technique is basically similar to those used throughout the European partners. Details will be given of the specimen geometry and preparation. In addition, the experimental test rig will be described. Examples of the information obtained from SP testing will be shown and they will be compared to data from "standard" creep testing techniques.

2 SP TEST SPECIMENS

One of the main advantages of the SP, and indeed other miniature testing techniques, is the fact that small amounts of material can be fully utilised with minimal wastage. With its roots in the nuclear inspection industry where the obtained material is both hard to get and limited in supply, [4], SP testing utilises specimens that can be machined from either small off-cuts of material taken using saws or boat cutters or by using specialised hemispherical cutters, such as SSAM [5] or spark erosion such as those developed by CESI [6]. Figure 1 illustrates an example of the specimen used in the UW Swansea's contribution to the EPERC SP test round-robin programme [6] and for comparison shows a "scoop" cut by a SSAM hemispherical cutter. Such a cut scoop, which is approximately 25mm in diameter and 5mm thick, would allow at least 3 disc SP samples to be manufactured.

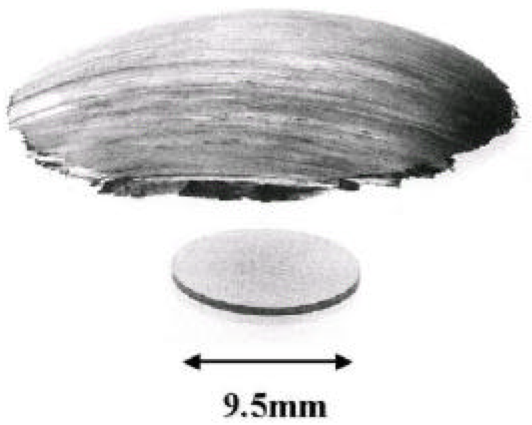

Figure 1: An example of a "scoop" cut with a hemispherical cutter next to an SP test specimen.

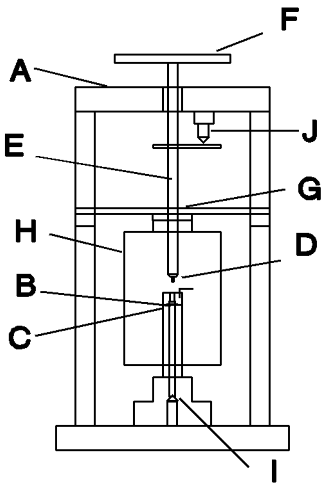

Figure 2: Schematic illustration of the Small Punch (SP) Experimental Test Rig.

The miniature specimens used are disc shaped with a diameter of 9.5mm and a thickness of 500 ±5µm. Specimen preparation involves machining the discs to a thickness of 700µm followed by hand grinding in a specially designed holder to the final dimensions. The grinding is undertaken with progressively finer grit papers (to reduce surface effects) until the final finish is achieved with a 1200 grit fine paper. Other research centres have used specimens with slightly differing dimensions, such as a diameter of 8mm with a thickness of 0.5mm [7]. It should be noted that in addition to creep, the SP test technique can be applied to the assessment of other mechanical properties [8,9]. This field of interest also takes full advantage of the small size of small disc shaped specimens to replace relatively large standard geometries such as Charpy specimens.

3 SP EXPERIMENTAL TEST RIG

Testing at UW Swansea is undertaken on a specially designed and manufactured test rig, shown schematically in Figure 2. The rig consists of a sturdy steel frame (A, Figure 2) which incorporates a stable base plate. The disc specimen (B) is placed in a lower die/holder which locates the specimen in the centre of the rig and applies a circumferential clamping load to hold the disc securely during loading (C). Load is applied to the disc using a 2mm diameter hemispherical Nimonic punch (D). The punch is attached to a vertical ram (E) which transmits the applied load in the form of calibrated lead weights placed on the load pan (F). A cross-beam (G) with low friction bearings is located in the centre of the frame to ensure that the load is applied directly through the rig's central axis. Heat is applied using a single zone furnace (H) controlled by a programmable digital controller. To allow for a degree of redundancy, the displacement of the disc under load is measured at two locations using ASL^{TM} capacitance transducers. One measurement (I) is taken from the upper punch while the second measurement (J) is taken directly from the disc via a quartz rod that is in direct contact with the lower surface of the disc. Time:

displacement data is recorded at intervals ranging from 20 to 5000 seconds using a PC based data logger. Testing can undertaken on discs in air and argon atmospheres at a range of loads and at temperatures up to 750?C.

4 EXPERIMENTAL RESULTS

Data is acquired continually during testing using computer based data logging. Figure 3 illustrates a typical creep curve from an SP creep disc test. It can be seen in figure 3 that both the transducer taking readings directly from contact with the lower surface of the disc and the transducer located on the upper ram both give very similar results. Generally the primary data is recorded from the lower transducer and the upper ram transducer is used to provide a degree of redundancy. However it can be seen from the data that both transducer locations provide good, reproducible data.

The creep curves recorded show initial primary, steady state secondary and final tertiary stages of creep deformation. This curve shape is directly comparable to the curves generated from standard uniaxial creep testing [10]. Indeed values of "minimum displacement rate" for SP creep tests can be obtained by calculating the slope of the secondary steady state region of the creep curve (mm/hour) in a manner similar to that performed for standard uniaxial tests, expressed as "/hour". It is generally accepted that there is an established link between the minimum creep rate and it's associated development of creep cavitation damage and the failure life. This relationship is known as the Monkman-Grant relationship [11] and states that the minimum creep rate is inversely proportional to the failure life. Figure 4 shows data for a number of uniaxial creep tests performed on low alloy steels found in power plant. Data is expressed in the form of minimum creep rate (/hr) vs. failure life. The data can be seen to follow the Monkman-Grant relationship which links the development of creep damage to failure life. Figure 4 also shows data from SP creep disc tests. The deformation (i.e. creep) rate is expressed as "mm/hour" and it can be seen to also follow the Monkman-Grant relationship indicating that the damage mechanisms operating within the disc specimen during testing are similar to those seen in traditional uniaxial creep tests.

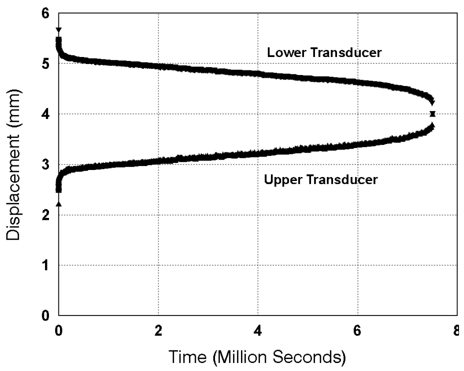

Figure 3: An example of the time/displacement data acquired from a creep SP test.

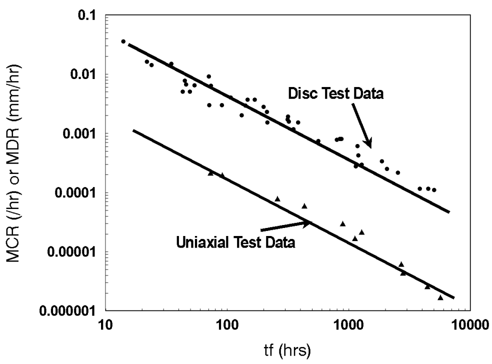

Figure 4: Data showing the Monkman-Grant relationships for uniaxial and disc SP tests on power station low alloy steels.

The claim that SP creep test discs are subject to creep cavitation is further supported by metallographic observations of specimens from SP creep tests which were interrupted during testing in argon, i.e. surfaces free of oxidation, Figure 5a&b.

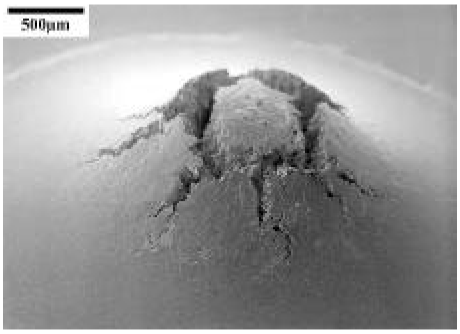

Figure 5a: Surface of bulged SP disc interrupted during testing.

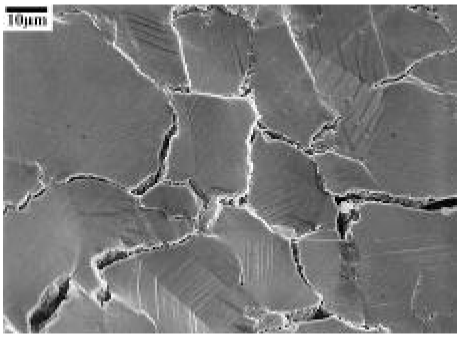

Figure 5b: Micrograph of the surface of an interrupted disc SP specimen showing grain boundary creep cavitation.

In these samples, grain boundary creep cavitation was clearly observed, Figure 5. In addition to exhibiting creep deformation behaviour that is analogous to uniaxial creep testing, SP disc creep tests at a range of conditions also display load and temperature dependences to the stress and temperature dependences of standard uniaxial tests. Comparisons between Norton-type power-law "n" values and Arrhenius activation energy "Q" values for tests on the same material using SP disc and uniaxial creep test have shown the values to be very similar [12].

5 CONCLUSIONS AND FUTURE AIMS

The SP disc testing at UW Swansea and partner laboratories has shown that the SP creep testing technique has the potential to be a powerful tool for the condition assessment of a range of materials and applications.

The key benefits are:

- The mechanisms of deformation and failure in SP disc tests are similar to established trends for standard uniaxial creep tests.
- Disc test results are reproducible and can accurately measure creep life.
- The methodology is now available to support run/repair/replace decisions.
- Establishing component-specific damage and key properties using miniature samples can provide major benefit to safe, reliable, and cost-effective operation of high energy plant.

In addition to creep life assessment in power and petrochemical plant, the SP technique has potential applications in a range of industries including aerospace and biomedical.

The current state of the SP disc creep programme has shown that the technique has matured to become a reproducible method of creep testing. Results have shown that it is successful in assessing the creep damage in a range of steel alloys. In addition to creep test, the miniature disc specimens can also be used to assess mechanical properties such as fracture toughness.

Programmes are currently underway across Europe which address a number of issues concerning the SP disc creep testing technique. These include the evaluation and calculation of the complex bi-axial stress systems within the disc during deformation by the application of an analytical membrane stress model [7] and large multi-lab test and evaluation programmes which assess the suitability of the technique [6].

In addition, current interest in the SP technique involves the potential development of a European standard for SP disc creep testing. This will define the main factors involved in SP testing (such as the specimen size, indenter size etc) with the aim of producing a methodology which will be acceptable to the range of agency who currently accept standard uniaxial creep tests as the main form of life assessment testing.

6 ACKNOWLEDGEMENTS

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