Small sample analysis of plant components subject to high temperature and pressure

In this technical article, *African Fusion* summarises work done by the eNtsa team at Nelson Mandela University, with Sasol Synfuels Operations and Eskom, around the development and implementation of small sample testing for critical components subject to high temperatures and pressures.

For middle to 'aged' industrial plants, advancements in metallurgical methods and analytical techniques have led to the reassessment of safety margins and, in some cases, the extension of operating plant life. Knowledge of material degradation and how it influences mechanical properties is essential when evaluating the risks associated with a plant life extension.

A barrier to the type of testing required for such assessments is often the large volumes of material required, which is usually not possible to obtain while plants are in service. Small sample testing, such as Small Punch Testing (SPT) and Small Punch Creep Testing (SPCT), presents an alternative means of obtaining the critical mechanical properties from small material samples.

Sample removal techniques, such as the scoop sampling process and the more recent WeldCore® procedure for the removal of a sample core followed by its immediate repair, now allow for in-service testing with semi- to non-destructive sample extraction.

The maturity of any degradation such as graphitisation or creep damage within structural components occurs locally within the bulk material of a component.

Figure 1: EDM Scoop Sampler with HMI and Control Trolley (Inset -EDM Scoop or 'boat' sample)

The extent to which this degradation influences the service life can be examined on a small scale using small punch testing (SPT) for static properties and small punch creep testing (SPCT) for creep behaviour.

Time dependent properties, such as creep testing, as well as time independent properties such as yield stress, tensile stress, ductile to brittle transition temperature and fracture toughness are now being calculated using various methods associated with SPT. Being able to reliably measure fracture toughness is vital to the design, maintenance and life extension processes and is currently a research focus of the group.

Extraction of small samples can be divided into two categories, namely shallow and deep extraction. Shallow extraction is typically done by scoop sampling or electrode discharge machining (EDM). This type of extraction does not require a weld repair procedure post extraction as the structural damage is contained within the surface and is usually not considered detrimental for continued operation.

For *in situ* deep sample extraction, WeldCore® core sampling and repair is now widely preferred for extracting cores of 8.0 mm in diameter in the petrochemical and power generation industries in South Africa.

Sampling and repair procedures

The methodology of small sample extraction from engineering components is driven by the need to obtain a sufficiently large sample for extracting material data to inform engineering decisions. Preferably, the extraction must be done in situ and currently two possible methods are available; first, shallow sampling, in which a small amount of material is removed to obviate the need for a weld repair; and second, deep sampling, which involves a coring approach followed by an in situ weld repair procedure before bringing the plant back into service.

Both shallow and a deep sampling techniques are being used with great success by the eNtsa technology group in South Africa. The shallow sample technique makes use of a compact purpose-build EDM wire cutting device to extract 'boat' samples of material, while the deep sample extraction is done with the WeldCore® process, which extracts a cylindrical core 8.0 mm in diameter.

The small sample geometry needed for both SPT and SPCT materials testing is disc shaped, typically with a diameter of 8.0 mm and a thickness of 500 µm.

Sample extraction methodologies

EDM for shallow applications

eNtsa has developed an EDM platform for extracting boat shaped material samples (Figure 1), which has a dedicated control platform for site work and uses an easily reconfigurable installation strategy to match specific site conditions.

These platforms utilise a cam based system to extract shallow samples of a predetermined geometry. The excavated scoop sample geometry can have a flat base with a width ranging from 10 to 30 mm, a length of 20 to 40 mm and a depth from 1.5 to 5.0 mm.

WeldCore for deep sample extraction and repair

WeldCore® technology was developed as an in situ material sampling and repair procedure. Sample retrieval and associated hole geometry are crucial for extracting a representative core containing material information from the depth of a component wall.

The final hole geometry needs to accommodate the removal and extraction of an 8.0 mm core. This is retrieved using a patented removal tool, providing an undercut to the core prior to removal. The length of the core to be removed depends on the material thickness at the removal site. This depth is calculated to leave a ligament of material sufficiently rigid to support the initiation of the solid state weld repair process.

Once the core has been successfully removed the final hole geometry is achieved by a custom made finishing tool, before repairing the extraction site. The repair weld associated with WeldCore® is based on Friction Hydro Pillar Processing (FHPP), a solid state welding process. This repair procedure has been adopted in ASME IX, where applicable it is applied with an appropriate pre- and post-weld heat treatment.

Figure 2: Schematic illustrating the WeldCore® process with photos of actual site procedure stages.

Figure 3: In-situ installation of WeldCore 3 Platform on a steam pipe.

The WeldCore® sampling and repair platform has a modular design for ease of handling at heights and accurate positioning in various onsite configurations. Sample retrieval is done at an exact identified position to gain maximum data value from the core. On welded thick-walled steam lines, sampling is typically focused on the heat-affected zone adjacent to conventional circular and longitudinal fabrication welds.

The process generally commences by placing a positioning fixture over the identified sample area to ensure that the exact location is sampled. The platform is then assembled over the sample site and the WeldCore® sampling process sequence commences.

SPT measurements from small disc test samples

From both cylindrical WeldCore® samples and boat shaped EDM samples, disc shaped test samples of 8.0 mm with a thickness of 500 µm are prepared for small sample testing. eNtsa at the Nelson Mandela University focuses on two methodologies: for static properties, Small Punch Testing (SPT) is used, while for time temperature behaviour the Small Punch Creep Test (SPCT) is employed. These small disc test samples are also used for obtaining metallurgical, chemical and hardness data.

Typically, the cylindrical or boat sample will be carefully evaluated prior to removing a disc for testing. When basing engineering decisions on a small volume of material, all information in the vicinity of final disc extraction must be known. Where applicable, eNtsa makes use of X- Ray tomography (CT scanning) as a decision making tool to identify regions containing defects to accurately identify the position for the removal of a test disc.

Static property analysis via Small Punch Test

The SPT method was initially designed to derive critical strain energy density measurements to quantify initiation fracture toughness on service exposed material. The method involves finite element modelling to estimate static material properties.

The testing apparatus and data analysis used comprises three major components: a static tensile/compression test platform; a specially designed small punch test fixture with an integrated digital microscope; and advanced software for simulation and analytical assessment. eNtsa uses a Universal Testing Machine with the required outputs from the machine: force and displacement. The SPT fixture also accommodates an integrated digital microscope in order to visually identify the occurrence of crack initiation (Figure 4).

The software used for the analysis component at eNtsa is Siemens' NX NASTRAN. Nonlinear material properties are generated using a purpose developed calculator built on the principals of the Ramberg-Osgood model, which is used to describe the non-linear relationship between stress and strain.

The procedure for testing SPT samples and arriving at estimated properties was adapted from the analytical approach suggested by Purdy et al: Increasing Reliability of Small Punch Fracture Toughness Testing

Figure 4: The SPT fixture, designed and fabricated by eNTSA for small disc testing.

with Acoustic Emission Monitoring. The first step is to perform a physical test on the disc (Figure 5), which is used to plot an experimental small punch curve, of punch load (N) versus displacement (mm) (Figure 6).

The next phase of analysis is aimed at determining the material's nonlinear stress and strain properties using the axisymmetric finite element model, before the actual physical punch test characteristics are modelled by calculating the nonlinear material properties via the Ramberg-Osgood functions. The nonlinear parameters are adjusted until the response suitably matches the actual load versus displacement results. This correlation in actual versus simulated results is shown in Figure 6. When the simulation results suitably match the test curve up to the region of crack initiation, then the calculated parameters are considered usable for further analyses.

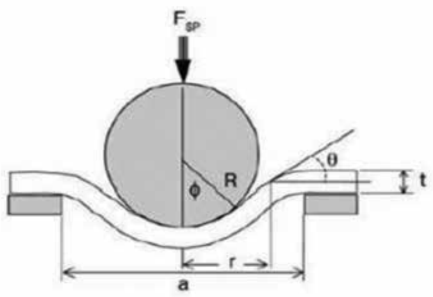

Figure 5: Schematic illustration of applying the punch load via a ball onto the SP Disc.

From a very early stage in eNtsa's involvement with the SPT methodology it was decided to focus on strain energy density as a ranking tool rather than attempting to quantify fracture toughness. The ability of the eNtsa SPT platform to provide a synchronised video of the real-time digital microscope image with the load/displacement curve assists in accurately identifying critical crack initiation during post-test evaluation. With this information the critical strain energy density (wc) can be calculated, which can be used as a ranking tool for describing the qualitative toughness of plant material.

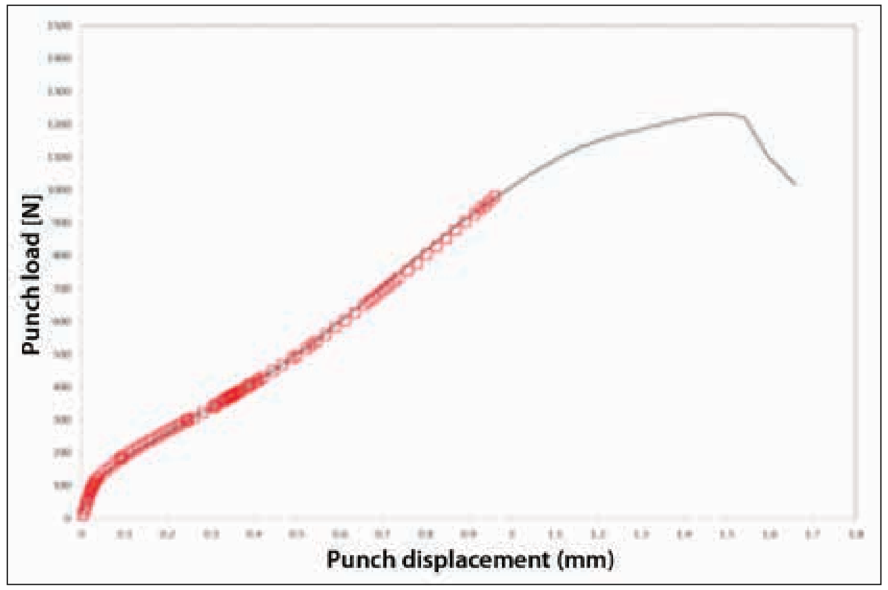

Figure 6: SPT load versus displacement data (blackline) with modification of the nonlinear material properties to achieve a suitable load versus displacement correlation superimposed (red circles).

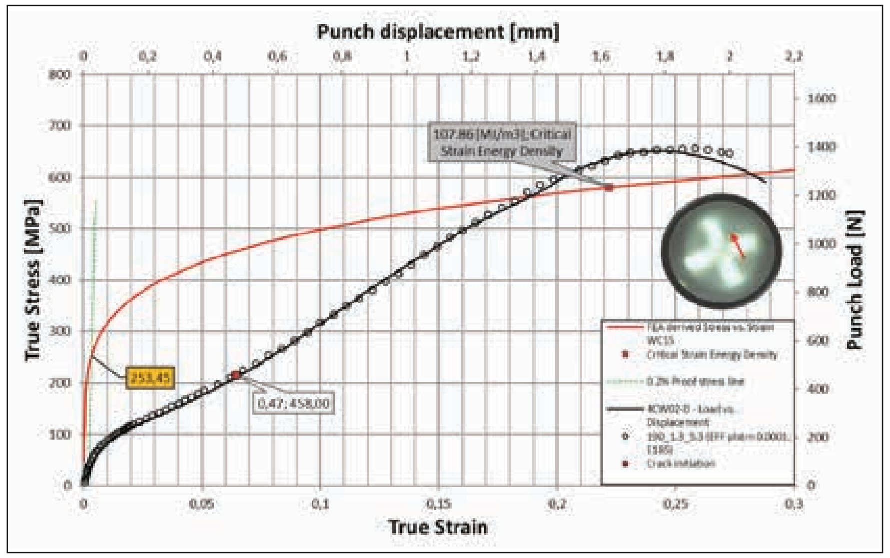

Figure 7: Typical Engineering data extracted from SPT after converting Punch load/deflection to Stress/Strain data.

In his work on the effect of graphitisation on the fracture toughness, Grewar – *Modelling the Effect of Graphitization on the Fracture Toughness (J_IC) of Service Exposed ASTM A-515 Gr. 65 material by the Small Punch Test Method* – also showed good correlation between Yield Strength measured by traditional methods versus Yield Strength estimated using small punch test analysis. The data as presented in Figure 7 shows the correlation between punch load and deflection data on the same graph as the true stress and strain plot, demonstrating that the simulation method enables SPT alone to be used to determine material properties for stress versus strain.

Creep property analysis and SPCT

A typical Small Punch Creep Testing (SPCT) sample is the same as that used for SPT (see Figure 8). eNtsa has developed and is running a fleet of sixteen SPCT platforms that use a ceramic ball and punch to generate creep data for both the petrochemical and power generation industries. Key design aspects of the include:

- A lever arm mechanism for dead weight loading.
- A ceramic ball-punch configuration.
- An argon purged sample furnace.
- Inline load monitoring.
- Deflection monitoring via the punch rod.
- Dual, indirect sample temperature control & monitoring.

Test sample preparation, calibration and meticulous loading and control of all parameters, variables and test environment are critical for obtaining repeatability in this type of test setup and environment.

As part of a validation process for the SPCT methodology, eNtsa first embarked on a zero creep life study by doing tests on a section of material known to have failed in service due to creep exhaustion. The zero creep life aimed to determine whether a decrease in life to rupture could be observed as samples are approaching the failure region. This rupture curve of zero-creep samples at the point of failure would then represent the zero creep life 'end point' for ongoing SPCT tests.

For the zero-creep test, a sample was removed from a ruptured carbon steel steam pipe bend as shown in Figure 9. Core samples were taken adjacent to the creep failure either side of point B2 where plastic thinning was clearly visible.

The SPCT Weldcore samples were removed in the radial direction and disc samples taken from mid-thickness, where the most damage was observed. Small punch creep tests were carried out on the samples using test conditions that would accelerate the failure.

Position B1, B4 and B5 achieved SPCT rupture times of 57, 60 and 56 hours respectively, while B3 achieved 40 hours and B2, where the rupture occurred, achieved 16 hours. Samples from the opposite side of the weld (A1 and A2) achieved in access of 1 000 hours at the same condition. From the data it was clear that areas that experienced the most creep damage achieved the lowest rupture time.

Figure 8: Two views of eNtsa's fleet of SPCT platforms.

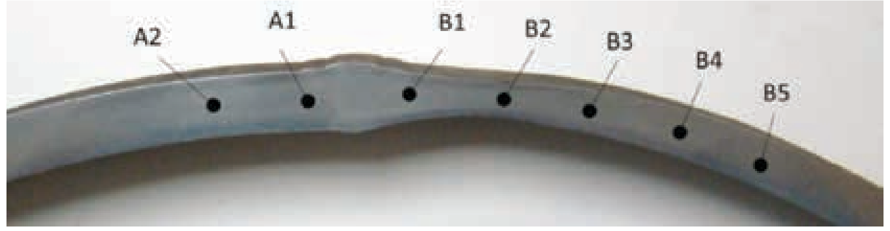

Figure 9: The ruptured pipe section used for the zero creep life study. Failure occurred at position B2.

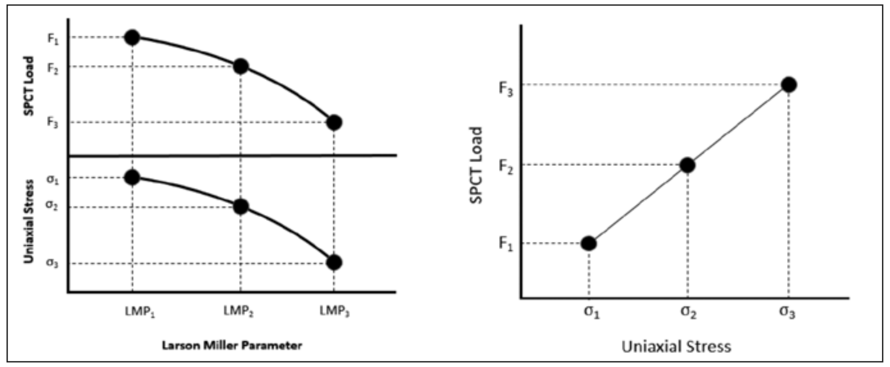

Figure 10: Derivation of the SPCT load versus Equivalent Uniaxial stress relationship using the Larson Miller Parameter.

Remaining Life estimation using SPCT data

The goal with creep testing is ultimately to reach a point where a remaining life can be estimated. In essence, SPCT methodology looks at the time versus temperature characteristic as a function of stress. The approach currently adopted for linking SPCT load data to uniaxial stress data, as described by Izaki et al – A creep life assessment method for boiler pipes using small punch creep test – entails obtaining SPCT data at various loads using a reference test material. From the test temperature and rupture time, the Larson-Miller parameter (LMP) is calculated for each load as described by the equation below:

$LMP = (\log t_r + C)\,T = f(\sigma)$,

where:

t_r is the rupture time (hours)

C is the Larson-Miller material constant

T is the absolute test temperature

Since a material exhibits only a single LMP value for each stress, the LMP value from the SPC Test is set equal to the corresponding LMP reference curve derived from uniaxial testing and the stress versus load relationship as derived for a wider stress range. The result is therefore a reference LMP curve expressed in both SPCT load and uniaxial stress. This method is illustrated in Figure 10.

Once the reference curve has been established for virgin (undamaged) material, the serviced exposed material can be tested and compared to the reference curve through the Larsen-Miller parameter to estimate the life fraction lost during service.

This LMP model is a simple and effective rupture model that presently yields fairly comparable results to remaining life estimations derived from uniaxial tests. Available uniaxial creep data for the steels being tested are fairly limited however, and the SPC test is still being refined and validated against uniaxial test data as it becomes available.

Conclusions

With acceptance of the WeldCore® process as part of the ASME IX welding code, the collection of representative bulk small samples followed by an immediate repair become a valuable tool for analysing the ongoing safety of plant components.

Initially used for the assessment of creep damage, developments in small punch testing for both static and creep purposes has enabled further value of small sample testing to be unlocked. Additionally, developments with regard to shallow sample removal by electro-discharge machining is now available.

Small sample testing has proved to be highly useful in determining both time independent and time dependent mechanical properties of mid-term and aging plant components.

Extracted from the paper: INTEGRITY AND REMAINING LIFE ASSESSMENT THROUGH SMALL SAMPLE ANALYSIS OF HIGH TEMPERATURE AND PRESSURE ENGINEERING COMPONENTS; DG Hattingh, S Grewar, D Bernard, IN Wedderburn, DJ. Erasmus and C Orsmond; 2nd International Conference on Structural Integrity for Offshore Energy Industry: 9-10 September 2019, Aberdeen