Monitoring of crack growth and crack mouth opening displacement in compact tension specimens at high temperatures

Development and implementation of the Direct Current Potential Drop (DCPD) method

Övervakning av spricktillväxt samt spricköppning av kompakta spänningsprover vid höga temperaturer

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ABSTRACT

The mechanical engineering department at the University of Idaho is conducting a project with the purpose of developing a complete system for investigating creep-, creep-fatigue- and fatigue properties of metallic materials at elevated temperatures up to 650 °C with Compact Tension (CT) specimens. Considerable efforts have been made to study and understand these phenomena, although numerous problems still exist. It is important to explore more extensively the complicated phenomena of creep, fatigue and of creep-fatigue interactions.

The Direct Current Potential Drop (DCPD) method is a common method used to investigate, for example, the initiation of cracks, crack growth rates and to monitor crack growth. The technique utilizes the fact that the electrical resistance of a CT specimen changes with crack growth. By applying a constant current over the specimen and measuring the resulting voltage over the crack, the crack length can be related to the voltage, and the difference in crack length with difference in voltage.

Standards from the American Society for Testing of Materials (ASTM) were used as guidance when designing the DCPD system and CT specimen. The development and implementation processes were divided into an analytical and an experimental stage. The final product consisted of a high temperature extensometer, to measure crack mouth opening displacement (CMOD), and a DCPD system, to measure crack growth, controlled by separate control units. The DCPD system consisted of a DC supply and a nano voltmeter along with Constantan wire and NiCr60 wire respectively, that were mechanically fastened.

The DCPD system delivered overall satisfying results and was able to generate sufficient data to produce a crack growth curve, \( \frac{da}{dN} \) vs. \( \Delta K \). Although, by taking advantage of resistance welding equipment to attach the DCPD wires, along with implementing one shared control unit for the DCPD system and the extensometer, more accurate and accessible measurements and correlations could be extracted.
SAMMANFATTNING


Standarder från American Society for Testing of Materials (ASTM) användes för att designa ett DCPD system samt en CT provstav. Utvecklings- och implementeringsprocessen var uppdelad i en analytisk och en experimentell del. Den slutgiltiga produkten bestod av en extensometer, för mätning av spricköppning vid höga temperaturer, och ett DCPD system, för mätning av spricktillväxt vid höga temperaturer, vilka kontrollerades av separata kontrollenheter. DCPD systemet bestod av en strömkälla och en nanovoltmeter tillsammans med Constantan kablar respektive NiCr60 kablar, vilka fastsätttes mekaniskt.

DCPD systemet levererade generellt sett tillfredsställande resultat och hade kapacitet att generera tillräckligt precisa data för att producera en spricktillväxtkurva, \( \frac{da}{dN} vs. \Delta K \). Däremot, genom att utnyttja en resistanssvets, för att fastsätta DCPD-kablarna, tillsammans med en gemensam kontrollenhet för extensometern och DCPD systemet, kan det tänkas att bättre och mer tillgängliga resultat kunde åstadkommas.
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NOMENCLATURE

\[ \dot{\varepsilon}_{ss} \quad \text{creep rate} \quad \text{hr}^{-1} \]
\[ A \quad \text{creep material constant} \quad \text{MPa}^{-n} \text{hr}^{-1} \]
\[ n \quad \text{stress exponent} \]
\[ \sigma \quad \text{stress} \quad \text{MPa} \]
\[ C^* \quad \text{Steady state creep fracture mechanics parameter} \quad \text{N/(mm*hr)} \]
\[ P \quad \text{applied load} \quad \text{N} \]
\[ T \quad \text{temperature} \quad \text{’C} \]
\[ \dot{V} \quad \text{CMOD rate} \quad \text{mm/hr} \]
\[ B \quad \text{depth of specimen} \quad \text{mm} \]
\[ B_N \quad \text{depth of specimen at V-grove} \quad \text{mm} \]
\[ W \quad \text{width of specimen} \quad \text{mm} \]
\[ L \quad \text{length of specimen} \quad \text{mm} \]
\[ a \quad \text{crack length} \quad \text{mm} \]
\[ a_i \quad \text{initial crack length} \quad \text{mm} \]
\[ a_f \quad \text{final crack length} \quad \text{mm} \]
\[ \Delta a \quad \text{crack length difference} \quad \text{mm} \]
\[ h_1 \quad \text{dimensionless function of creep exponent n and geometric parameter } a/W \]
\[ \eta_1 \quad \text{dimensionless parameter} \]
\[ \delta_{e} \quad \text{elastic CMOD} \quad \text{mm} \]
\[ \delta_{p} \quad \text{plastic CMOD} \quad \text{mm} \]
\[ P' \quad \text{load distributed over length} \quad \text{N/mm} \]
\[ E \quad \text{Young’s modulus} \quad \text{MPa} \]
\[ T(a) \quad \text{geometry dependent factor} \]
\[ K \quad \text{stress intensity factor} \quad \text{MPa}\sqrt{m} \]
\[ K_{1C} \quad \text{fracture toughness} \quad \text{MPa}\sqrt{m} \]
\[ f(a) \quad \text{geometry dependent factor} \]
\[ R \quad \text{electric resistance} \quad \text{Ω} \]
\[ \rho \quad \text{electric resistivity} \quad \text{Ωm} \]
\[ A_{cs} \quad \text{cross-sectional area} \quad \text{m}^2 \]
\[ V \quad \text{voltage} \quad \text{microvolt, } \mu\text{V} \]
\[ V_i \quad \text{initial voltage} \quad \text{microvolt, } \mu\text{V} \]
\[ V_f \quad \text{final voltage} \quad \text{microvolt, } \mu\text{V} \]
\[ I \quad \text{current} \quad \text{ampere, A} \]
\[ t_{\text{hold}} \quad \text{hold time} \quad \text{s} \]
\[ R \quad \text{loading ratio} \]
1. INTRODUCTION

1.1 Creep and crack size measurement

The mechanical engineering department at the University of Idaho is conducting a project with the purpose of developing a complete system for investigating creep-, creep-fatigue- and fatigue-properties of metallic materials at elevated temperatures up to 650 °C. These complex behaviors in engineering components are especially important to take into consideration at certain service temperatures and environments. Creep and fatigue can cause failure of a component or a system if neglected and usually incur great financial penalties. Creep, fatigue and aggressive environments stands for most of the failures in components at elevated temperatures. The processes involved in the failures may act independently or interactively. To ensure the longevity and safe operation of a nuclear power plant for instance, it is essential to prevent these processes and evaluate creep-fatigue life. Although considerable efforts have been made to study and understand these phenomena, numerous problems still exist. It is important to explore more extensively the complicated phenomena of creep, fatigue and of creep-fatigue interactions. [1]

Creep is a time dependent deformation of a material under a constant load. That is, it is deformation which occurs as a function of time due to sustained stress. It normally occurs more easily at elevated temperatures, but can be an issue even at room temperatures. Creep occurs in three stages; Primary Creep, Steady-State Creep and Tertiary Creep. As an approximation it can be stated that creep becomes a design concern when service temperatures exceed 35 % of the melting point of the alloy from which the component is made. Figure 1 presents a schematic diagram of creep-test, illustrating the three stages of creep.

![Figure 1: Schematic diagram of creep test, illustrating the three stages of creep. [2]](image)

Fatigue damage, as opposed to creep deformation, is generated by a cyclic stress and depends primarily on plastic strain. When the two damage components act in a combined manner, creep-fatigue interactive events occur. Creep-fatigue damage happens in many service conditions such as, for example, steam turbine components, gas turbines and pressure vessels. [1][2][3][4]

The life of components which are subjected to creep deformation can be estimated from creep rupture data, an approach that has been used in engineering analyses for several decades. Although, high temperatures components, especially those containing thick sections, do not always fail due to creep rupture. These
components are subjected to stress and temperature gradients, and are more likely to fail due to developed cracks at high stress locations which propagates and ultimately causes failure. Failure can also result from pre-existing defects on the material, in which case the entire life time of the component is consumed with crack propagation. Creep rupture data can only take so much into consideration, and it is therefore important to develop the capability to predict crack propagation life at elevated temperatures in the presence of creep deformation. [3]

When investigating creep, creep-fatigue and fatigue properties, the American Society for Testing of Materials (ASTM) has developed three standards; ASTM647, ASTM-E1457 and ASTM E2760-10 which are commonly used and accepted by the research society. [5][6][7]

It has been shown that creep crack growth rate data can be correlated using the C* parameter. By correlating the C* parameter with crack growth rate data one can use the C* parameter to predict component failure for instance. For a material obeying Norton’s creep law, shown in Equation 3, and is tested using CT specimens, the C* value is related and calculated from the Crack Mouth Opening Displacement (CMOD) rate, $\dot{V}$, according to Equation 2. [3][8][9]

$$\dot{\varepsilon}_{ss} = A \sigma^n$$  \hspace{1cm} (1)

$$C^* = \frac{\rho \dot{V}}{b(W-a)} \left(2 + 0.522 \left(1 - \frac{a}{W}\right)\right) \frac{n}{n+1}$$  \hspace{1cm} (2)

C* can also be estimated numerically using Equation 3 below,

$$C^* = A(W-a) h_1 \left(\frac{a}{W}, n\right) \left(\frac{\rho}{1.455 \eta_1 \theta(W-a)}\right)^{n+1}$$  \hspace{1cm} (3)

, where $\eta_1$ for a CT specimen is given by

$$\eta_1 = \left(\frac{2a}{W-a}\right)^2 + 2 \left(\frac{2a}{W-a}\right) + 2 \right)^{1/2} - \left(\frac{2a}{W-a}\right) + 1$$  \hspace{1cm} (4)

The parameter $h_1$ is a dimensionless function of the creep exponent $n$ and geometric parameter $a/W$. $h_1$ for compact specimen in plane stress is obtained through interpolation from Kumar et.al. (1981), Table 3-2. [10][11]

To measure and investigate creep-, creep-fatigue- and fatigue-properties of metallic materials, compact tension (CT) testing can be done using a servo hydraulic load frame, which can be programmed to perform required operations such as, for example, load cycles, constant loads and hold times. To create the high temperature environment a furnace can be used in conjunction with the servo hydraulic load frame. [12]

In order to measure crack growth rates of a specimen placed inside a furnace, an alternative technique to observation has to be implemented. Electrical Potential Difference (EPD) is a common method used to investigate, for example, the initiation of cracks, crack growth rates and to monitor crack growth. The most common and easy EPD technique, which is to be developed in this thesis, is the Direct Current Potential Drop (DCPD) method. This is a technique which has been used with satisfying results for several decades. The technique utilizes the fact that the electrical resistance of a CT specimen change with crack growth. By applying a constant current over the specimen and measuring the resulting voltage over the crack, the crack length can be related to the voltage, and the difference in crack length with difference in voltage. The equipment utilized in a
DCPD system is summarized by a constant DC supply, a voltmeter, current input wires and voltage pick-up wires. See Figure 2 for a basic schematic drawing of a DCPD system. [5][13]

![Figure 2: Schematic drawing of a DCPD system, including DC supply, recording device, voltmeter and a CT specimen with the direction of crack growth, a, illustrated.](image)

By using the equipment mentioned above in creep, fatigue and creep-fatigue tests, a wide range of data can be collected. Saxena and Narasimhachary (2013) and Piard et al. (2004) presents interesting results regarding creep and creep-fatigue crack growth. These results show the relation between several factors, such as number of cycle (N), crack length/current potential drop, time, crack growth rate and stress intensity factor range (ΔK), as shown in Figure 3-7. [10][14]

![Figure 3: Load line elastic and creep displacement as a function of elapsed cycles. Open symbols refer to instantaneous elastic displacement and the closed symbols refer to the creep displacement during the hold time.](image)
Figure 4: Fatigue crack growth rate as a function of $\Delta K$. [10]

Figure 5: Average time rate of crack growth during hold time as a function of $\Delta K$. [10]

Figure 6: Crack advance over time divided into a reloading part ($\Delta a_{FR}$) and a hold time part ($\Delta a_{HT}$). [14]
1.2 Purpose and goal
The purpose of this thesis is to support the development and implementation of systems capable of monitoring crack growth and CMOD in CT specimens at high temperatures. The goals of this thesis were:

1. Develop and implement a DCPD system with the ability to monitor and measure crack length as well as detecting crack length increments of 0.1 mm in a creep-fatigue test with CT specimens at any given time or cycle at temperatures up to 650 °C.
2. Validate the developed DCPD system to ensure that it has the ability to monitor and measure crack length as well as detecting crack length increments of 0.1 mm in a creep-fatigue test with CT specimens at any given time or cycle at temperatures up to 650 °C.
3. Implement an extensometer designed for monitoring of CMOD at any given time or cycle in a creep-fatigue test with CT specimens with a precision of at temperatures up to 650 °C.

2. THEORY OF TEST METHODS

2.1 CT testing
CT testing is a test method commonly used to investigate mechanical properties of metallic materials. Properties normally investigated are creep, creep-fatigue, and fatigue properties. The American Society for Testing of Materials (ASTM) has developed three standards which are accepted and used in the academic world:

1. ASTM E647-00: Standard Test Method for Measurement of Fatigue Crack Growth Rates
2. ASTM E1457-00: Standard Test Method for Measurement of Creep Crack Growth Times and Rates in Metals

The specimens used in each test method, called CT specimens, have standardized dimensions and tolerances specified in each standard. The differences between each standard specimen are small and the general theory of how they work remain the same. [5][6][7]

Figure 7: Creep-fatigue crack growth rate for different hold times as a function of ΔK. [14]
The notched specimen is fixed in a servo hydraulic load frame and then subjected to a load $P$ across the crack mouth opening. Depending on the test method utilized, $P$ can for instance be a constant load, a cyclic load or a combination of the two. When subjected to the load, the specimen will deform as a function of time, $t$, as well as a function of load cycles, $N$. There will be elastic and plastic CMOD, $\delta_e$ and $\delta_p$, and crack growth. The cause and type of crack growth are dependent on the type of test method being utilized. $P$, $t$, $N$, $\delta_e$, $\delta_p$, and $a$ are all documented throughout the testing and thereafter used to calculate sought data, such CMOD rate, $\dot{V}$, $C^*$, and crack growth, $Aa$. [5][6][7]

The CMOD, during testing, can be monitored and measured using an extensometer. An extensometer is a strain gaged device, making it compatible with any electronics designed for strain gaged transducers. Most often they are connected to a test machine controller, such as the MTS test machine controller. [15]

The CMOD can be divided into two types of deformation; elastic deformation and plastic deformation, both of which can be estimated analytically. The elastic deformation can be estimated with Equation 5 [16],

$$\delta_{el} = \frac{P'}{E} T(a)$$  \hspace{1cm} (5)

where $P'$ and $T(x)$ are defined as Equation 6 and 7,

$$P' = \frac{P}{B}$$  \hspace{1cm} (6)

$$T(a) = \left(1 + \frac{a}{W} \right)^2 \left( 2.1630 + 12.219 \frac{a}{W} - 20.065 \left( \frac{a}{W} \right)^2 - 0.9925 \left( \frac{a}{W} \right)^3 + 20.609 \left( \frac{a}{W} \right)^4 - 9.9314 \left( \frac{a}{W} \right)^5 \right)$$  \hspace{1cm} (7)

The total plastic deformation can be estimated by integrating the CMOD rate, developed from Equation 2 and presented below as Equation 8, over a crack length interval.

$$\dot{V}(a) = \frac{C^*(W-a)}{(2+0.522(1-\frac{a}{W}))^{(\frac{a}{W})^{0.5}} \sqrt{\frac{a}{W}}}$$  \hspace{1cm} (8)

Another way to estimate the plastic CMOD over a specified hold time is to multiply the CMOD rate at an arbitrary crack length, $a$, with the hold time, $t_{hold}$, according to Equation 9. It is then assumed that the CMOD rate does not change over $t_{hold}$.

$$\delta_{cr} = \dot{V}(a) t_{hold}$$  \hspace{1cm} (9)

When designing the test, it is crucial that the stress intensity factor, $K_I$, as well as the fracture toughness, $K_{IC}$, of the material are known or can be determined. The load, together with initial and final crack length, can be adjusted to achieve a desired initial and final $K_I$. If $K_I$ is too low, the crack will not propagate. If $K_I$ is too high, $K_I > K_{IC}$, the crack will cause final fracture. $K_I$ can be calculated with Equation 10,

$$K_I = \frac{P}{B \sqrt{W} \sqrt{f(a/W)}}$$  \hspace{1cm} (10)

where $f(a/W)$ is given by

$$f \left( \frac{a}{W} \right) = \left( \frac{2 - a/W}{1 - a/W} \right)^2 \left( 0.886 + 4.64 \frac{a}{W} - 13.32 \left( \frac{a}{W} \right)^2 + 14.72 \left( \frac{a}{W} \right)^3 - 5.6 \left( \frac{a}{W} \right)^4 \right)$$  \hspace{1cm} (11)
Before conducting any tests, the specimen is pre-cracked using fatigue loading according to test standard. The importance of fatigue pre-cracking is “to provide a sharpened fatigue crack of adequate size and straightness which ensures that: 1) the effect of the machined starter notch is removed from the specimen, 2) and that the effects on subsequent crack growth rate data caused by changing crack front shape or pre-crack load history are eliminated. When the test is completed, the specimen is cracked open using fatigue loading once again in order to physically measure Δa” (ASTM Standard E647-00 2003). [5]

The initial crack length and the final crack length in creep-fatigue testing depends on the user requirements as well as the relation between $K_I$ and $K_{IC}$ of the material. The user has to make sure that $K_I$ at the tip of the crack does not exceed $K_{IC}$ of the material at the end of the test. Common $a$, lies between 16-20 mm and common Δa lies between 10-13 mm. [8][10]

2.2 DCPD – Direct Current Potential Drop

The DCPD method involves passing a constant current through a pre-cracked test specimen which is subjected to a load and measuring the potential difference across the crack. As the crack propagates, the un-cracked cross sectional area of the specimen decreases leading to an increase in electrical resistance, thus the potential difference between each side of the crack increases. [5][13]

The relation between the un-cracked cross sectional area is presented in Equation 12,

$$ R = \frac{\rho L}{A_{cs}} \quad (12) $$

Furthermore, the un-cracked cross sectional area, $A_{cs}$ in a CT specimen, is defined as the smallest cross-sectional area through which the current has to pass. $A_{cs}$ is calculated according to Equation 13,

$$ A_{cs} = B(W - a) \quad (13) $$

The voltage over the crack, as a constant direct current is passed through the specimen, is related to the electrical resistance according to Ohm’s law,

$$ V = RI \quad (14) $$

By combining Equation 12, 13 and 14, and by letting the voltage be a function of crack length, the voltage can be written as Equation 15.

$$ V(a) = I \left( \frac{\rho L}{\frac{B}{W-a} A_{cs}} \right) \quad (15) $$

The relationship between the voltage over the crack and the crack length can be approximated through a linear interpolation, as shown in Equation 16. [5]

$$ a = a_s + (a_f - a_s) \left( \frac{V - V_s}{V_f - V_s} \right) \quad (16) $$

By dividing Equation 15, $V(a)$, with Equation 15, $V(a_s)$, an alternative expression for approximating the relationship between the voltage over the crack and the crack length can be derived1, as shown in Equation 17.

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1 See Appendix A for proof.
\[ a = a_s + \left( a_f - a_s \right) \left( \frac{v - V_s}{V_f - V_s} \right) \left( \frac{V_f}{V_f - V_s} \right) \] 

(17)

The technique is extremely sensitive. A potential difference corresponding to a crack increment of 0.05 mm may be detected with suitable instrumentation, but a calibration curve is necessary to convert the potential measurements to crack lengths and crack growth rates. According to Johnson (1965), the calibration, as well as the electric potential data, is independent of material chemistry, heat treatment and thickness of the specimen. In this thesis, crack increments of 0.1 mm are to be evaluated. [17]

The output voltages are typically in the 0.100 to 50.0 mV range for common current magnitudes (5 to 50 A), specimen dimensions and materials. Precise measurements, typically ± 0.1 %, of these relatively small output voltages must be made to obtain accurate crack size values. Furthermore, reducing electrical noise and drift is necessary to obtain sufficient voltage resolution. [5]

One or more measurements of the crack size should be made during the test using an alternative technique, optical measurements for instance, in order to ensure that the crack sizes determined from electric potential measurements are correct. If optical measurements cannot be made during the test, the final crack size, along with initial starter crack size, should be compared to the crack sizes determined from electric potential measurements. If a difference is observed between the optical and the EPD crack sizes, a linear correction factor must be employed to post-correct the EPD crack size values. [5]

2.2.1 DC supply
Any suitable constant DC supply may be used if it has sufficient long and short term stability. The required stability is a function of the resolution of the voltage measurement equipment and the desired crack size resolution. For optimum conditions, the relative stability of the power supply should be equal to the effective resolution of the voltage measurements system. [5]

2.2.2 Voltage measurement equipment
Any equipment which has sufficient resolution, accuracy and stability characteristics may be used. For DC systems, the equipment is required to be able to measure small changes in DC voltage, 0.05 to 0.5 µV, with relatively low DC signal to AC RMS noise ratios. [5]

Three commonly used systems are [5]:

1. Autographic recorder: Commonly available with suitable sensitivity and can be used to record the output voltage directly from the specimen. A preamplifier can be used to boost the direct voltage output from the specimen before recording.
2. Preamplifier to boost the direct output voltage from the specimen to a level that can be digitized using a conventional analog to digital (A/D) converter and microcomputer.
3. Digital voltmeter with a digital output capability. The advantage of this system is that all of the sensitive analog circuits are contained within a single instrument.

2.2.3 Recording device
A recording device is required in order to store the results from the measurements. The voltmeter can with advantage function as a recording device. [5]
2.2.4 *Wire selection and attachment*

In aggressive environments, such as elevated temperatures, factors such as strength, melting point and oxidation resistance of the wires must be taken into account. Aggressive test environments may require special lead wire materials or coatings, or both, in order to avoid loss of electrical continuity caused by corrosion for instance. Selection of current input wire should be based on current carrying ability, and ease of attachment (weldability, connector compatibility). Wires must be of sufficient wire gage to carry the required current under test conditions and may be mechanically fastened or welded to the specimen or gripping apparatus. According to equi-potential patterns obtained for CT specimens, it is shown that a greater sensitivity is reached by introducing the current through the top surface than through the side flanks. In the side flanks the potential gradients in the vicinity of the probes are so shallow that only a slight increase in potential is obtained for small crack extensions. The current lead should be attached through welding or soldering to ensure a good connection. If this is not possible, due to material restrictions for instance, point application of current through a single screw is recommended. Example of potential probes: Platinum wires, 0.1 mm diameter with position placement on specimen identified by small Vickers indents. The control of the power used to weld the probes on the specimen surface is crucial. The weld acts like a microstructural notch and may have an impact on the material creep/fatigue behavior. [5][13]

Voltage wires should be as fine as possible to allow precise location on the specimen and minimize stress on the wires caused by fatigue loading, which could cause detachment. Ideally, the voltage wires should be resistance welded to the specimen to ensure a reliable, consistent joint. If weldability is limited, the voltage wires may be fastened using mechanical fasteners. The most suitable positioning for the potential measurement wires is close to the notch on the top of the surface. Attachment close to the crack tip is also possible. This would give more sensitive results but would also lead to larger errors from any slight variations in positioning of the probes from specimen to specimen. Probes positioned close to the crack tip are also more sensitive to crack tip plasticity, which can be confused with increase in crack length. [5][13]

The use of graphitized electrical analogue paper in order to determine the optimal positions for the input of current has proved to be invaluable in previous work. The analogue technique is able to indicate the positions of the lines of equi-potential inside the fracture specimen when a constant current is flowing through it. *Ritchie et al. (1971)* presents two such patterns in his paper, illustrated in Figure 8, with the current introduced through the top surface (a) and through the side flanks (b). [13]

![Figure 8: Equi-potential distribution for CT specimens, un-cracked and cracked, with different current input positions.][1]

[1]: Figure 8: Equi-potential distribution for CT specimens, un-cracked and cracked, with different current input positions. [13]
Ritchie et al. (1971) concludes that case (a) is the more optimal one due to the reason that this position for the input current provide more sensitive results than for case (b), where the potential gradients in the vicinity of the probes are so shallow that only a slight increase in potential is obtained for small crack extensions. Very low sensitivity is achieved for the initial stages of crack growth when case (b) is utilized. [13]

2.2.5 Calibration
A calibrated curve may be obtained by measuring the potential distributions in a standard specimen containing narrow slots or cracks of accurately known lengths. On way of achieving this in a compact tension test specimen is to fatigue pre-crack the specimen using a high frequency, approximately 100 Hz, cyclic loading at room temperature. The pre-cracked length does not have to be more than about 2 mm. It is important that the cyclic load during the final 0.5 mm pre-crack growth does not exceed 60% of the load to be applied during creep crack growth testing. Creep testing is then conducted to the specimen, but terminated well before final fracture is likely to occur, using EPD to monitor the potential difference as the crack grows. Finally, the specimen is subjected to high frequency cyclic loading until final fracture occurs. The initial crack length and final crack length can then be measured and correlated to the measured potential difference. Equation 17 presents a relationship between crack growth and variation of potential drop. Although, a linear relationship between the crack growth, Δa, and the variation of potential drop can be assumed, Equation 16, if Δa / a_s ≤ 0.2. It has been shown that, for simple specimen geometries, theoretical calculations agree well with experimental calibrations. [6][8][13][17]

2.2.6 Factors which affect the measured voltage
The DCPD method is susceptible to thermoelectric effects. This means that additional DC potentials are produced, in addition to the applied potential, due to specimen electric field. These thermoelectric voltages can be a substantial fraction of the total measured voltage and should be accounted for. Due to the fact that the thermoelectric effect is present even without the applied potential this phenomenon can be accounted for by subtracting the voltage measured without any applied potential to the voltage measured with applied voltage. [5]

Changes in the instrumentation or in the specimen may result in proportional changes in the measured voltage. For example, a small change in specimen temperature can result in a few μV change in EPD signal due to the change in the material’s electrical resistivity. Also, some materials exhibit time-dependent conductivity changes while at elevated temperatures. Variations in the gain of amplifiers or calibration of voltmeters may also result in a proportional scaling of the measured voltages. This can be compensated for by normalizing the voltage measurements using additional voltage measurements taken at a reference location. The reference location can be on the same specimen or on an alternative specimen in the same environment. If the reference measurements are made directly on the test specimen, the location must be chosen so that the reference voltage is not affected by crack size. Use of reference voltage measurements can significantly increase crack size resolution. [5]

3. EXPERIMENTAL

3.1 Specimen design
The ASTM standards provided samples of standard specimen geometries, e.g. Figure 9, which illustrated a standard specimen according to the standard ASTM E2760-10 for creep-fatigue crack growth testing. With
ASTM standards as guidelines, a creep-fatigue specimen\(^2\) was designed and implemented, as shown in Figure 10. Relevant specimen dimensions used in the analytical approximation, if nothing else is specified, are provided in Table 1. The specimen features an Electrical Discharge Machined (EDM) notch at the tip of the crack, as well as a 60° V-grove along the full width of the specimen to ensure crack initiation and crack propagation along the center line. The material utilized in the experimental part of this thesis was the stainless steel grade AISI 316. [7]

\(^2\) See Appendix B for specimen specifications.
Table 1: Creep-Fatigue fracture specimen dimensions.

<table>
<thead>
<tr>
<th>Specimen Feature</th>
<th>Dimension, mm (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, W</td>
<td>50.0 (2)</td>
</tr>
<tr>
<td>Depth, B</td>
<td>12.0 (0.5)</td>
</tr>
<tr>
<td>Depth at V-grove, B_N</td>
<td>10.0 (0.42)</td>
</tr>
<tr>
<td>Length, L</td>
<td>60.0 (2.4)</td>
</tr>
<tr>
<td>Notch depth to width ratio, a/W</td>
<td>0.30</td>
</tr>
</tbody>
</table>

3.2 Analytical approximations of CMOD

CMOD is experimentally measured by an extensometer. Analytical approximations of the elastic and plastic CMODs were performed in order to conclude what requirements, such as measuring range, the extensometer need to meet. All tests were performed considering different combinations of applied loads, crack lengths and hold times. Only the extreme conditions were tested, i.e. the largest estimated crack lengths and the initial crack lengths. All the tests were performed using the material constants $A$ and $n$, used in Norton’s creep equation, as well as the Young’s modulus, at 625 °C, derived for P91 steel by Saxena and Narasimhachary (2013). A summary of test conditions for all the tests is given in Table 2. [10]

Table 2: Material data used in each approximation of CMOD for P91 CT specimen at 625 °C. [10]

<table>
<thead>
<tr>
<th>Test</th>
<th>$P$</th>
<th>$t_{\text{hold}}$</th>
<th>$a$</th>
<th>$h_1$</th>
<th>$K_1$</th>
<th>$C^*$</th>
<th>$A$</th>
<th>$n$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7500</td>
<td>600</td>
<td>20.0</td>
<td>0.565</td>
<td>21.8</td>
<td>$1.20 \times 10^{-2}$</td>
<td>9.53 $\times 10^{-21}$</td>
<td>8.24</td>
<td>125000</td>
</tr>
<tr>
<td>2</td>
<td>7500</td>
<td>600</td>
<td>27.0</td>
<td>0.522</td>
<td>33.0</td>
<td>$2.28 \times 10^{0}$</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>3</td>
<td>7500</td>
<td>600</td>
<td>30.0</td>
<td>0.543</td>
<td>41.0</td>
<td>$3.67 \times 10^{1}$</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>4</td>
<td>4500</td>
<td>600</td>
<td>15.0</td>
<td>0.731</td>
<td>10.1</td>
<td>$5.81 \times 10^{-6}$</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>5</td>
<td>4500</td>
<td>600</td>
<td>30.0</td>
<td>0.543</td>
<td>24.6</td>
<td>$0.32 \times 10^{0}$</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>6</td>
<td>9000</td>
<td>600</td>
<td>15.0</td>
<td>0.731</td>
<td>20.2</td>
<td>$3.51 \times 10^{-3}$</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>7</td>
<td>9000</td>
<td>600</td>
<td>30.0</td>
<td>0.543</td>
<td>49.2</td>
<td>$1.98 \times 10^{2}$</td>
<td>“”</td>
<td>“”</td>
<td>“”</td>
</tr>
</tbody>
</table>

The material constants $A$ and $n$, used in Norton’s creep Equation, as well as the Young’s modulus at 625 °C, were taken from Saxena and Narasimhachary (2013), Table 2. [10]

Each elastic CMOD was calculated from Equation 5, while each plastic displacement was approximated with Equation 9. The total CMOD in each test was finally determined by adding the elastic displacement to the plastic displacement.

3.3 DCPD – Voltage Outputs

As a crack propagates in a stainless steel CT specimen, with a constant current passing through it, the voltage measured over the crack is changed as a result of the change in electrical resistance, which in turn is a result of the cross sectional area being reduced. Analytical voltages over different crack lengths of interest, as a constant current of 4A was passed through the CT specimen, were calculated with Equation 15. The electrical resistivity used in the calculations were $\rho = 69 \times 10^{-8}$ $\Omega$m for material class stainless steels. [18]
3.4 DCPD – Proof of Concept

In order to verify that the DCPD method work in practice, an experimental setup was created in which the theory was tested on stainless steel-, carbon steel- and aluminum- foil/plate specimens of different depths. By testing on different materials with different depths, more investigations and comparisons could be made between the analytical approximations and the experimental data. The width and the length of the specimens were the same as for the actual CT specimen, specified in Figure 10. By using foil/plate specimens, a crack growth can easier be created by using a knife or a plyer, depending on the depth. The specimens were cut out from bigger sheets and pre-cracked 20 mm from the load line, which is 32.5 mm from the edge of the specimen. No other preparation was needed. The specimen was then fastened centered in the fixture, as shown in Figure 12. The materials and their respective relevant properties and the applied current used for the validation of DCPD method are presented in Table 3. The resistivity values presented for each material class are taken from literature and are only to be seen as representative values for each material class. [18]

Table 3: Parameters used for the test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Material class</th>
<th>( \rho ) (( \Omega m ))</th>
<th>( B )</th>
<th>( a_s )</th>
<th>( a_f )</th>
<th>( \Delta a )</th>
<th>( I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Steel</td>
<td>( 69.0 \times 10^{-8} )</td>
<td>0.570</td>
<td>20.0</td>
<td>35.0</td>
<td>5.00</td>
<td>4.00</td>
</tr>
<tr>
<td>2</td>
<td>Carbon Steel</td>
<td>( 14.3 \times 10^{-8} )</td>
<td>0.150</td>
<td>20.0</td>
<td>35.0</td>
<td>5.00</td>
<td>4.00</td>
</tr>
<tr>
<td>3</td>
<td>Carbon Steel</td>
<td>( 14.3 \times 10^{-8} )</td>
<td>0.058</td>
<td>20.0</td>
<td>35.0</td>
<td>5.00</td>
<td>4.00</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum</td>
<td>( 2.82 \times 10^{-8} )</td>
<td>0.028</td>
<td>20.0</td>
<td>48.0</td>
<td>2.00</td>
<td>4.00</td>
</tr>
<tr>
<td>5</td>
<td>Carbon Steel</td>
<td>( 14.3 \times 10^{-8} )</td>
<td>9.55</td>
<td>20.0</td>
<td>20.0</td>
<td>0.00</td>
<td>4.00</td>
</tr>
</tbody>
</table>

These approximated voltages calculated in 6.3 DCPD – Voltage Outputs were used as a guidance in the process of selecting an appropriate power supply and voltmeter to use in the experiment.

The power supply and voltmeter used in the experiment were the following:

- **Power supply**: Delta Elektronika SM 7020-D
- **Voltmeter**: HP Multimeter 3458

The following experimental procedure was applied for each crack length in test 1-4:

1. Specimen attached in a fixture \(^3\).
2. Specimen subjected to a constant current, \( I = 4 \ A \), via copper bars in fixture.
3. Voltage over the crack was measured and recorded every minute for a total of five minutes, after which an average voltage was calculated.

In addition to the procedure above, the theoretical voltages over each crack was calculated according to Equation 16, in which \( V_s \) and \( V_f \) were taken from the experimental results, and according to Equation 17, in which \( V_s \) and \( V_f \)

\(^3\) See Appendix C for fixture specifications.
were estimated using Equation 15. This was done in order to evaluate which of the two interpolations represented the reality more accurately.

Figure 11 and 12 illustrates the experimental setup: power supply, voltmeter and specimen fixture. The specimens were attached in the fixture using copper bars, which in turn were connected to the power supply using alligator clips and common laboratory wiring. Alligator clips were used for simplicity. The same type of alligator clips and wiring were also used for the connection between the specimen and the voltmeter.

![Experimental setup for proof of concept procedure.](image1)

**Figure 11: Experimental setup for proof of concept procedure.**

![Fixture used in the proof of concept process.](image2)

**Figure 12: Fixture used in the proof of concept process.**

3.5 Experimental Setup – Description of system components

3.5.1 DCPD - Power supply

The DCPD system used a **Keithley 2280S-32-6 Precision Measurement DC Supply** provided by Tektronix. This model can output up to 32V at 6A and uses linear regulation to ensure low output noise. The icon-based menu provides all the functions users can control and program for fast access to source setup. The power supply is controlled manually⁴ from the menu and the buttons provided on the front panel. Any external control software is not utilized. The front panel also features connector ports for the current output. Figure 13 illustrates the power supply and Table 4 presents relevant product data. [19]

---

⁴ See Appendix D.1: Keithley 2280S-32-6 DC supply – Manual Control Instructions.
When the supply current was set to 4A, the resulting voltage readings were in the order of 400 – 600μV according to Equation 15. From the data provided with the power supply it was observed that a maximum deviation in sourced current would not exceed 10mA. A deviation of 10mA in a sourced current of 4A would result in a change in voltage reading of 1μV, according Equation 15. According to Equation 15, a deviation of the current of ±10mA would not interfere with the range of interest when it comes to the output voltages in the process of monitoring the crack growth, and was therefore approved.

3.5.2 DCPD – Voltmeter

The DCPD system used a Keithley 2182A Nano voltmeter, provided by Tektronix, due to its capacity of detecting voltages in the nV-scale with very low noise and drift. This model is optimized for making stable, low noise voltage measurements reliably and repeatedly. It provides higher measurement speed and significantly better noise performance than alternative low voltage measurements solutions. Measurements can be recorded in the voltmeters buffer, capacity of 1024 readings, meaning that an external recording device is not necessary. The voltmeter features a display which allows for the user to monitor the voltage readings as they take place and view the set settings. Figure 14 illustrates the nano voltmeter and Table 5 presents relevant product data.[20]
A data acquisition software is recommended for external control and data acquisition. In this thesis, LabVIEW\textsuperscript{5} is utilized due to its versatile functions and availability.

3.5.3 DCPD - Wire selection and attachment

Combinations of three types of 26 American Wire Gauge (AWG\textsuperscript{6}) wire of different materials were selected as potential DCPD wires, namely K-type thermocouple-, NiCr60- and Constantan- wire. These wires have high resistivity and good stability at high temperatures. The investigation is mentioned in more detail in section 3.6 DCPD – Testing of Stability. The wires were mechanically fastened by wrapping them around stainless steel screws one lap. The placements of the DC supply wires and the voltage pick-up wires were determined using ASTM standard recommendations\textsuperscript{7}.

3.5.4 Extensometer

In the experimental study, a Model 3548COD High Temperature Furnace COD Gage, provided by Epsilon Technology Corp, were used to measure CMOD. The extensometer was for use up to 1200°C and were specifically designed for fracture mechanics testing. This was a strain gage device, requiring electronics designed for strain gaged transducers.

A DSCUSB Strain Gage to USB Converter, provided by Mantracourt, is used as the signal conditioner and allows for the user to easily connect the equipment directly to a computer via USB. With the DSCUSB module comes DSCUSB Toolkit: Version 4.0.0, an easy-to-use software, which allows configuration, calibration, logging and parameter management of the DSCUSB module.

\textsuperscript{5} See appendix D.2: Keithley 2182A Nanovoltmeter – LabVIEW Instructions.
\textsuperscript{6} 26 AWG is equal to a diameter of 0.405 mm.
\textsuperscript{7} See Appendix E for attachment and positioning of DC supply- and voltage pick-up- wires.
3.5.5 Extensometer – Attachment and calibration

The extensometer was attached to the furnace via its integrated mounting bracket and an external aluminum bracket, as shown in Figure 15. The internal mounting bracket allowed for placement adjustments in x and y direction, and the external aluminum bracket allowed for placement adjustments in z direction, considering a Cartesian coordinate system according to the own featured in Figure 15.

![Figure 15: Epsilon 3548COD High Temperature Furnace COD Gage, with high temperature ceramic extension arms, attached to the Furnace via an aluminum bracket.](image)

Calibration was done through the provided DSCUSB Toolkit: Version 4.0.0 software along with two known distances, one lower than the theoretical $CMOD_{min}$ and one larger than the theoretical $CMOD_{max}$, in order to ensure that the extensometer will be able to measure the desired intervals.

3.5.6 Overview System Description

The extensometer and the DCPD system was incorporated together with a servo hydraulic load frame, provided by MTS, featuring a water cooling system, and a Split Tube Furnace, provided by Applied Test Systems (ATS). A complete overview of the experimental setup is shown in Figure 16. Figure 17 displays the CT specimen setup, with the specimen fastened in the servo hydraulic load frame and with attached DCPD wiring. The specimen in Figure 17 has gone through a test and is cracked. Table 6 and Table 7 presents relevant equipment specifications for the load frame and the furnace.
Figure 16: Complete experimental setup, featuring the DCPD system, the extensometer, the load frame, and the furnace.

Figure 17: CT specimen setup, with specimen attached in the servo hydraulic load frame via load grips and with DCPD wiring attached.
Table 6: Servo hydraulic load frame specifications.

<table>
<thead>
<tr>
<th>Servo hydraulic load frame</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model/Series</strong></td>
</tr>
<tr>
<td><strong>Load Capacity (ton / kip)</strong></td>
</tr>
<tr>
<td><strong>Control Unit</strong></td>
</tr>
<tr>
<td><strong>Control Software</strong></td>
</tr>
<tr>
<td><strong>Grips</strong></td>
</tr>
</tbody>
</table>

Table 7: ATS Split Tube Furnace, Model 3210, specifications.

<table>
<thead>
<tr>
<th>ATS Split Tube Furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model/Series</strong></td>
</tr>
<tr>
<td><strong>Watts</strong></td>
</tr>
<tr>
<td><strong>Volts</strong></td>
</tr>
<tr>
<td><strong>Amps</strong></td>
</tr>
<tr>
<td><strong>Max. Temperature (C)</strong></td>
</tr>
<tr>
<td><strong>Control Unit</strong></td>
</tr>
</tbody>
</table>

3.6 DCPD – Testing of stability

In order to ensure that the DCPD system can be used with good reliability and deliver reliable results, tests were conducted with the purpose of investigating the stability of the DCPD system, when operating at high temperatures, and how different wires affected the stability. Table 8 specifies the tests conducted and the DC supply- and the voltage pick-up wires utilized in each test.

Table 8: Testing of DCPD stability for different wire configurations.

<table>
<thead>
<tr>
<th>Test</th>
<th>Wire, DC supply (I) &amp; Voltage Pick-Up (V)</th>
<th>Test Conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I: K-Type Thermocouple, V: K-Type Thermocouple</td>
<td>Heat up RT - 650 °C, 10 000 sec</td>
</tr>
<tr>
<td>2</td>
<td>I: Constantan, V: NiCR60</td>
<td>Heat up RT - 650 °C, 10 000 sec</td>
</tr>
<tr>
<td>3</td>
<td>I: Constantan, V: Constantan</td>
<td>Heat up RT - 650 °C, 10 000 sec</td>
</tr>
<tr>
<td>4</td>
<td>I: Constantan, V: NiCR60</td>
<td>Stability at 650 °C, 100 sec</td>
</tr>
<tr>
<td>5</td>
<td>I: Constantan, V: Constantan</td>
<td>Stability at 650 °C, 100 sec</td>
</tr>
</tbody>
</table>

3.7 DCPD – Calibration

A calibration procedure was carried out, in accordance with the method described in 3.2.5 Calibration, including pre-cracking, fatigue cracking and loading until final fracture, followed by measuring and correlating crack lengths with recorded voltages. The procedure stages are stated in Table 9.
Table 9: DCPD calibration procedure stages.

<table>
<thead>
<tr>
<th>Calibration Stage</th>
<th>(P_{\text{max}})</th>
<th>(R)</th>
<th>Frequency (Hz)</th>
<th>(N)</th>
<th>(T)</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pre-cracking</td>
<td>10 000</td>
<td>0.1</td>
<td>25</td>
<td>44 000</td>
<td>RT</td>
<td>Initiate Crack</td>
</tr>
<tr>
<td>2. Pre-cracking</td>
<td>8 000</td>
<td>0.1</td>
<td>25</td>
<td>107 000</td>
<td>RT</td>
<td>Pre-cracking</td>
</tr>
<tr>
<td>3. Pre-cracking</td>
<td>6 000</td>
<td>0.1</td>
<td>25</td>
<td>28 000</td>
<td>RT</td>
<td>Create Beach Mark</td>
</tr>
<tr>
<td>4. Fatigue</td>
<td>8 000</td>
<td>0.1</td>
<td>15</td>
<td>23 500</td>
<td>600 °C</td>
<td>Fatigue Cracking</td>
</tr>
<tr>
<td>5. Final Fracture</td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
<td>RT</td>
<td>Final Fracture</td>
</tr>
</tbody>
</table>

4. RESULTS

4.1 Analytical approximations of CMOD

Table 10 presents the analytically derived elastic, \(\delta_{\text{el}}\), Equation 5, and plastic, \(\delta_{\text{cr}}\), Equation 9, CMODs, which depends on creep, for the different material data presented in Table 2.

Table 10: Analytical approximations of elastic and plastic CMODs of P91 CT specimen at 625 °C at seven load-crack length conditions.

<table>
<thead>
<tr>
<th>Test</th>
<th>(P)</th>
<th>(a)</th>
<th>(K_i)</th>
<th>(\delta_{\text{el}})</th>
<th>(\delta_{\text{cr}})</th>
<th>(\delta_{\text{tot}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>7500</td>
<td>20.0</td>
<td>21.8</td>
<td>0.110</td>
<td>4.85 (\times) 10^{-5}</td>
<td>0.110</td>
</tr>
<tr>
<td>2</td>
<td>7500</td>
<td>27.0</td>
<td>33.0</td>
<td>0.218</td>
<td>7.30 (\times) 10^{-3}</td>
<td>0.225</td>
</tr>
<tr>
<td>3</td>
<td>7500</td>
<td>30.0</td>
<td>41.0</td>
<td>0.304</td>
<td>1.04 (\times) 10^{-1}</td>
<td>0.408</td>
</tr>
<tr>
<td>4</td>
<td>4500</td>
<td>15.0</td>
<td>10.1</td>
<td>0.041</td>
<td>4.46 (\times) 10^{-8}</td>
<td>0.041</td>
</tr>
<tr>
<td>5</td>
<td>4500</td>
<td>30.0</td>
<td>24.6</td>
<td>0.182</td>
<td>1.54 (\times) 10^{-3}</td>
<td>0.184</td>
</tr>
<tr>
<td>6</td>
<td>9000</td>
<td>15.0</td>
<td>20.2</td>
<td>0.084</td>
<td>1.35 (\times) 10^{-5}</td>
<td>0.082</td>
</tr>
<tr>
<td>7</td>
<td>9000</td>
<td>30.0</td>
<td>49.2</td>
<td>0.365</td>
<td>4.65 (\times) 10^{-1}</td>
<td>0.830</td>
</tr>
</tbody>
</table>

4.2 DCPD – Voltage Output

Figure 18 presents calculated voltage readings as a function of crack length, \(V(a)\), according to Equation 15. The presented graph show voltage readings at crack lengths \(a = 15-35\ mm\), due to the fact that this is the interval of interest.

![Figure 18: Analytical voltage readings vs. crack length.](image-url)
4.3 DCPD – Proof of Concept

Figures 19-21 present graphical overviews of average voltages as functions of crack length for specimen 1 – 3, Table 3. The measured voltages, theoretical voltages according to Equation 16, linear interpolation, and the theoretical voltages according to Equation 17, non-linear interpolation, are represented in the graphs.

Figure 19: Measured voltage vs. crack length, stainless steel, specimen 1.

Figure 20: Measured voltage vs. crack length, carbon steel, specimen 2.
Figure 21: Measured voltage vs. crack length, carbon steel, specimen 3.

Figure 22 presents a graphical overview of the measured voltage as a function of crack length for specimen 4. The theoretical voltage as a function of crack length, according to Equation 17, non-linear interpolation, is presented in this figure. Furthermore, two linear interpolations with different end points are presented.

Figure 22: Measured voltage vs. crack length, aluminum, specimen 4.

4.4 DCPD – Testing of Stability

Figures 23 – 25 show the measured voltages vs. time as the specimen is being heated from room temperature to 650 °C as well as when the voltage is stabilizing after the goal temperature is reached, for three different wire configurations presented in Table 8.
Figure 23: Measured voltage over time as specimen is heated from RT – 650 °C, I & V: K-Type Thermocouple wire.

Figure 24: Measured voltage over time as specimen is heated from RT – 650 °C, I: Constantan, V: NiCr60.
Figure 25: Measured voltage over time as specimen is heated from RT – 650 °C, I & V: Constantan.

Figure 26 and 27 show the stability of the DCPD system at a constant temperature of 650 °C and for a fixed crack length, meaning without any load applied to the specimen, for two different wire configurations, presented in Table 8.

Figure 26: Measured voltage over time at steady temperature 650 °C, I: Constantan, V: NiCr60.
4.5 DCPD – Calibration

Figure 28 presents the measured voltage vs. time during the pre-cracking stage of the calibration process, where the specimen was cracked $\Delta a = 4\, \text{mm}$. The small shelf that can be observed at $V \approx 3\, \text{mV}$ is due to a stop in the pre-cracking procedure.

Figure 29 and 30 presents the measured voltage vs. time, and the CMOD respectively, during the fatigue stage of the calibration process.
Figure 29: Stage 4 in the calibration process, fatigue cracking 23 500 cycles at 600 °C.

Figure 30: CMOD as a function of time during stage 4 in calibration process, fatigue cracking 23 500 cycles at 600 °C.

Figure 31 illustrates the CT specimen used in the calibration process with three distinct sections in the fracture surface, namely the pre-cracking-, fatigue cracking- and final fracture- section.
Figure 31: CT specimen with three distinct sections in the fracture surface. Namely the pre-cracking-, fatigue cracking- and final fracture-section.

Table 11 presents the initial crack length and the final crack length and their corresponding measured voltages during the fatigue stage of the calibration process, along with the crack length at the end of the linear crack growth in the fatigue cracking process and its corresponding measured voltage.

**Table 11:** Calibration of DCPD system, voltage-crack length relationship according to Equation 17.

<table>
<thead>
<tr>
<th>Stage of fatigue cracking process</th>
<th>(a) (mm)</th>
<th>(V) (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiation</td>
<td>19.5</td>
<td>0</td>
</tr>
<tr>
<td>End of linear crack growth</td>
<td>30</td>
<td>101</td>
</tr>
<tr>
<td>Final</td>
<td>33</td>
<td>193</td>
</tr>
</tbody>
</table>

Figure 32 presents the crack growth per cycle as a function on the stress intensity, \(\Delta K\), at the tip of the crack, during the fatigue stage of the calibration process.
5. DISCUSSION

The CT specimen was designed in accordance with ASTM standards, and with ASTM E2760-10 guidelines in particular concerning the notch details (see Figure 9). Even though this standard standardize testing for creep-fatigue crack growth exclusively, the geometry requirements of the CT specimens specified in the standards ASTM E2760-10, ASTM E647-00 and ASTM E1457-00 have a generous overlap. Due to this overlap, it was possible to design a single CT specimen, Figure 10, which fulfilled the requirements for all three standards mentioned above. This allowed for time savings and, more importantly, financial savings. In addition to the ASTM guidelines, the CT specimen featured a 60˚ V-grove (Figure 10) along the full width of the specimen to ensure crack initiation and crack propagation along the center line. A V-grove in this fashion has been utilized by previous researchers in the field, with the same exact purpose, Saxena and Narasimhachary (2013) being one of them. The V-grove is accounted for and will not affect the CT specimen’s functionality or validation.

When analytically approximating CMOD, elastic and plastic, different extreme conditions were considered, including minimum and maximum loads, initial and final crack lengths and a specific hold time. These extreme conditions were considered, as opposed to any other given condition, due to the fact that it is at these conditions that the CMOD is at its minimum and maximum value respectively. The loads, crack lengths and hold time was set in conjunction between data from previous conducted research within the field, Saxena and Narasimhachary (2013) and Xia et.al. (1998) to name a few, and analytical calculations of the stress intensity factor, $K_I$, for each condition. The elastic CMOD was approximated through equation 5, a function of the crack length, $f(a)$, taken from Nonlinear Fracture Mechanics for Engineers, Saxena (1998). Although, the plastic CMOD was approximated through equation 9, which takes the average crack growth rate, $V$, at a given crack length and
multiplies it with the hold time. In reality, the crack growth rate changes with crack length for a given constant load. The material properties used were the materials properties of P91 steel, used in Saxena and Narasimhachary (2013). The properties of a P91 steel was considered to be adequate to use in the analytical calculations due to their similarities with the properties of the materials of interest to the University of Idaho. Furthermore, the material constants $A$ and $n$ used in Norton’s creep equation, as well as the Young’s modulus at 625 °C along with all the other assumptions, were considered good enough to use for approximating CMOD. This was considered due to the fact that the lone purpose of this activity was to investigate in what range the CMOD would be in future experiments and for different conditions, and not the exact CMOD for a given value. The results of the approximated minimum and maximum CMOD respectively was considered reasonable and were well within range for common high temperature extensometers.

Analytical voltages over different crack lengths of interest, as a constant current of 4A was passed through the CT specimen, were calculated with equation 15. This activity was necessary in order to determine what kind of voltmeter was required for the DCPD system. Equation 15, derived through equation 12, 13 and 14, builds on the theory that the voltage is dependent on the electrical resistance and the cross sectional area, which in turn is a function of the crack length, $f(a)$. The analytical output voltages fell within the range, specified in ASTM E647-00, and were very close to the experimental output voltages recorded during testing, arguing that the equation 15 was a close-to-reality model.

In order to verify that the DCPD method work in practice, an experimental setup was created in which the theory was tested. The setup was made for testing of the DCPD method on thin metal foil or plates, and not on actual CT specimens. The reason for this was simply the fact that it was easier to create crack growth in metal foil than in a thicker solid CT specimen. The theory behind the DCPD method remains the same, independent on specimen depth. The theory was tested on stainless steel-, carbon steel- and aluminum- specimens of different depths. By testing on different materials with different depths, more investigations and comparisons could be made between the analytical approximations and the experimental data. The power supply and the voltmeter used in this stage were provided by the University of Idaho, and met the required specifications on accuracy and precision, specified in ASTM E647-00. The foil specimens were connected to the power supply through copper bars and to the voltmeter through alligator clips. Neither of these connections, illustrated in Figure 12, met the recommendations for wire attachment, ASTM E647-00, and could not easily be re-produced. Although, since no comparison between the specimens tested were made at this stage, the connections were considered good enough.

The results achieved in the Proof-of-Concept activity, Figures 19 – 21, show that the concept of the DCPD method work, meaning that the voltage increase with crack length. From Figures 19 – 20, it can be seen that the measured voltage follows the linear interpolation, between voltage and crack length, better than the non-linear interpolation. At least past a crack length of approximately $a \approx 25$ mm. Before that point, it seems like both of the interpolations follow the measured voltage quite well. Looking at Figure 21, it can be seen that the measured voltage follows the linear interpolation up until a for a crack length of $a \approx 38$ mm, and then breaks of to follow the non-linear interpolation. From this observation it can be concluded that the measured voltage in specimen 1 - 3, Figures 19 – 21, most likely would follow the non-linear interpolation if the test would have continued to a longer crack length. Figure 21 also show, that for a crack length of $a \approx 30$ mm, the measured voltage follows the
linear and the non-linear interpolation. Considering the fact that creep-fatigue tests only goes to a crack length of approximately \( a \approx 30 \text{ mm} \), due to the fact that the stress intensity, \( K_i \), reaches a desired maximum value, the linear interpolation is accurate enough. Saxena and Narasimhachary (2013) as well as the standard ASTM E1457-00, argues that a linear interpolation is good enough. Slight offsets can be seen for the non-linear interpolations for all the specimens tested. These offsets are due to an inaccurate resistivity value in the analytical calculations. This does not change the relationship between the measured voltage and the non-linear interpolation.

When assembling the final DCPD system, the Keithley 2280S-32-6 Precision Measurement DC Supply was used to generate a steady current. This power supply performed above expectations, meaning above the set requirements, with very low noise levels and with high accuracy and precision. The instrument was easy to use and handle during testing. For measuring the voltage, a Keithley 2182A Nano volt meter was utilized. This instrument performed well and was able to detect and record the desired voltages, without any major deviations. The CMOD was measured and recorded through an extensometer with high accuracy and high precision. As oppose to the power supply and the voltmeter, the extensometer was designed to be used in these specific kind of tests, and it performed very well and was able to detect the CMOD changes of interest. When measuring the crack growth and the CMOD, during a creep-fatigue test for instance, it is of advantageous if the extensometer and the voltmeter, or DCPD system, run through the same control unit or software. By running the two systems from the same control unit, one can start the systems at the same time and with ease present, and relate, the crack growth and CMOD with each other. Unfortunately, in this case, the two systems are controlled through separate control units. This means that the operator need to manually relate the crack growth measurements with the CMOD measurements after each test, which in such a case would be possible source of error.

The stability of the DCPD system means the ability to record and keep stable voltage value, only dependent on the crack length change, at a constant furnace temperature. The stability of the DCPD system at high temperatures, 700 \(^\circ\)C, is, among other things, dependent on the material used in the DC supply wires and the voltage pick-up wires. An important reason for this is the materials sensitivity to resistivity changes due to temperature changes. When investigating the influence, on system stability, of different DC supply/pick-up wire combinations of Constantan-, NiCr60- and K-type thermocouple- wire, Table 8, significant variances can be observed. Figures 23 – 25 presents vast differences in voltage behavior depending on the wire selection. By comparing Figures 23 and 25, it can be observed that the voltage readings stabilize faster and with less noise, after reaching the set temperature, when only using Constantan, as opposed to only using K-type thermocouple wire. Moreover, Figure 24 suggests that by using Constantan as DC supply wire and NiCr60 wire as voltage pick-up wire, the voltage readings stabilize smoother and with even less noise than it does when only Constantan wire is being used. The reason for this is that NiCr60 is less prone to resistivity change when exposed to temperature changes at high temperatures. Also, when comparing the system stabilities for these two different wire configurations, at a constant temperature of 650 \(^\circ\)C, Figure 26 and 27, it is observed that a combination of Constantan and NiCr60 is much more stable than only Constantan, even though some random peaks are observed in Figure 26. What these peaks are caused by is unclear, but might depend on the mechanical connection between the specimen and the wires. The mechanical wire attachment was used due to welding restrictions with available welding equipment. Since welding is the recommended attachment method by the standard ASTM E647-00, purchasing a resistance welder might be a good investment, and might resolve these
random peaks. The selected wire gauge, 26 AWG, was considered fine enough to ensure precise and reproducible wire placement and attachment from specimen to specimen. Also, by using mechanical fasteners, the drilled screw holes will help reproducing the same wire attachment and placement even further.

When investigating three possible wire materials, it is easy to calculate that there are nine possible combinations. Only three combinations were tested, all with different voltage pick-up wires, since that wire had a bigger influence on voltage readings than the DC supply wire. The DC supply wire does not have that large influence since the DC supply managed to compensate for resistivity changes by varying output voltage and keeping the current steady. Also, NiCr60 wire as DC supply wire was not optimal due to the high resistivity, which would require a high output voltage. The materials investigated were chosen due their good high temperature properties, such as low sensitivity to resistivity changes due to temperature changes, in combination with affordability. A possible better material to use when it comes to high temperature properties, and recommended by the standard ASTM E647-00, would be Platinum. Platinum is extremely expensive though, and wasn’t considered at this stage due to financial limitations. Another way of eliminating the effects of resistivity change due to temperature changes was to take reference voltage measurements at a location not affected by the crack, and thereafter only record the voltage difference between the reference point and the measured voltage over the crack. This wasn’t done due to financial restrictions.

The first stage of the calibration process, the pre-cracking phase, showed a very stable crack growth over time with no excessive noise or disruption, as can be seen in Figure 28. Although a small shelf can be observed in Figure 28 which is due to a quick stop in the process. This stop was to optically ensure that crack initiation had taken place, and did not have any effect on the pre-cracking process. Followed the pre-cracking was the fatigue cracking, Figure 29. Looking at this curve, a steady crack growth can be seen here as well but with a more non-linear behavior than for the pre-cracking curve. Although, the crack seems to have grown quite linear up until a voltage reading of about 100 mV, after which the crack growth excels fast and a non-linear behavior is observed. This is due to a combination of a high $a/W$ ratio and a high stress intensity at the crack tip. The final voltage reading in Figure 29, also presented in Table 11, could be used in the non-linear interpolation to use as a calibration. Since this voltage corresponds to a crack length which is above the maximum crack length of interest, approximately 30 mm, another final voltage taken at the end of the linear part of the fatigue cracking curve, presented in Table 11, is recommended to use with the linear interpolation. This is an easier interpolation and also recommended by the standard ASTM E647-00. By using the same interpolation as other research institutes and facilities, a fairer comparison between different materials can be made. That is the main purpose with having standardized testing methods in the first place.

Figure 32 presents a fatigue crack growth curve, generated from the data recorded during the calibration process. It is shown that the crack growth increment per cycle increases with stress intensity, which corresponds well with what Saxena and Narasimhachary (2013) presents in Figure 5 for instance. This crack growth curve, along with the other results presented, show that the DCPD system is capable of monitoring crack length, crack growth and crack growth rate at any given time or cycle during a fatigue test with CT specimens at temperatures up to 650 °C.
6. CONCLUSION

1. A DCPD system with the ability to monitor and measure crack length as well as detecting crack length increments of 0.1 mm in a creep-fatigue test with CT specimens at any given time or cycle at temperatures up to 650 °C was designed and implemented.

2. Validation of the DCPD system has shown that the accuracy and sensitivity of the system meets the set requirements and that a liner correlation between voltage and crack length can be assumed.

3. Along with the DCPD system, an extensometer was implemented with the ability to monitor CMOD at any given time or cycle in a creep-fatigue test with CT specimens with a precision of at temperatures up to 650 °C. The DCPD system and the extensometer performed well and met the requirements.

4. Although, it is possible that by taking advantage of resistance welding equipment to attach the DCPD wires, along with implementing one shared control unit for the DCPD system and the extensometer, more accurate and accessible measurements and correlations could be achieved.
7. REFERENCES


\[ \frac{V}{W} = \frac{W - a}{W - a} \cdot \frac{W - a - c - a}{W - a} = 1 \cdot \frac{a - c}{W - a} \]
\[ \frac{W - a}{a - c} = V \cdot \frac{a}{W} \]
\[ W = a + (a - c) \left( \frac{V}{W} \right) \]
\[ a(V - Y) + \frac{W - a}{V} = a + (a - c) \left( \frac{V}{W} \right) \]
\[ \frac{dV}{dV} - \frac{aV}{V} \cdot \frac{aV}{V} = a + (a - c) \left( \frac{V}{W} \right) \]
\[ \frac{dV}{dV} - \frac{aV}{V} = a + (a - c) \left( \frac{V}{W} \right) \]
\[ aV = aV + aV \left( \frac{V}{V} \right) \]
\[ aV = aV + aV \left( \frac{V}{V} \right) \]
\[ aV = aV \left( \frac{V}{V} \right) + aV \left( \frac{V}{V} \right) \]
\[ aV = aV \left( \frac{V}{V} \right) + aV \left( \frac{V}{V} \right) \]
\[ aV = aV \left( \frac{V}{V} \right) + aV \left( \frac{V}{V} \right) \]
\[ aV = aV \left( \frac{V}{V} \right) + aV \left( \frac{V}{V} \right) \]
\[ aV = aV \left( \frac{V}{V} \right) + aV \left( \frac{V}{V} \right) \]
\[ aV = aV \left( \frac{V}{V} \right) + aV \left( \frac{V}{V} \right) \]
\[ aV = aV \left( \frac{V}{V} \right) + aV \left( \frac{V}{V} \right) \]
APPENDIX C.2 - PROOF OF CONCEPT – FIXTURE PLATE
DCPD Nanovoltmeter - Control in LabVIEW

Start up
1) Start “Nanovoltmeter” on desktop.
2) Open “Trigger Config.vi”.
   a. Set “delay (secs)” to desired measurement interval.
   b. Press \[ \rightarrow \] to finalize settings.
3) Open “Buffer Config.vi”.
   a. Set “Buffer Setup” to “Configure Buffers”.
   b. Set “Buffer Control” to “Next”.
4) Press \[ \rightarrow \] to start taking measurements. First Measurement will happen after first desired measurement interval. Example: If delay (secs) = 10 seconds, the first measurement will happen 10 seconds after you press \[ \rightarrow \].

Data acquisition
1) Open “Buffer Read.vi”.
   a. Press \[ \rightarrow \] to collect data from buffer.
   b. Right click on the frame above the collected data point, go to “Export”. Press “Export Data To Excel”, all according to the example below.
DCPD Current Supply - Control

Start up

The Keithley 2280S-32-6 Precision Measurement DC Supply will work as a constant current supply if the maximum current, I_{Limit}, is set to the required value and the voltage, V_{Sat}, is set high enough so that Ohms law restricts the voltage due to the resistance in the current supply wires. Now I_{Limit} will stay constant and the voltage will change inversely to the resistance, which will change due to temperature effects, according to Ohms’s law: \frac{V}{R} = I_{Limit}

1) Set "I_{Limit}" to the required current value, 2A for instance. (RED)
2) Set "V_{Sat}" to 16V. (BLUE)
3) Press "OUTPUT" to apply current. (GREEN)
APPENDIX E - ATTACHMENT AND POSITIONING OF CURRENT SUPPLY- AND VOLTAGE PICK-UP- WIRES

6 screws total:
2-56 UNC - 2B TAP \( \Phi \ 0.170 \)
450 DRILL ( 0.070 ) \( \Phi \ 0.210 \) - (1) HOLE

Steel: 2.5x2 and 0.5 in

KARLSTAD UNIVERSITY
CT Specimen - Holes

Drawing no.

CT version 1

Issue Sheet

APPENDIX F.1 - RESULTS – 7.2 DCPD – VOLTAGE OUTPUTS

Table: Theoretical voltage readings vs. crack length.

<table>
<thead>
<tr>
<th>a</th>
<th>20</th>
<th>20.1</th>
<th>25</th>
<th>25.1</th>
<th>30</th>
<th>30.1</th>
<th>35</th>
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</thead>
<tbody>
<tr>
<td>V(a)</td>
<td>0.442</td>
<td>0.443</td>
<td>0.530</td>
<td>0.532</td>
<td>0.662</td>
<td>0.666</td>
<td>0.883</td>
<td>0.889</td>
</tr>
</tbody>
</table>
### APPENDIX F.2 - RESULTS – 7.3 DCPD – PROOF OF CONCEPT

Table: Measured voltage ratio at given crack length in specimen 1.

<table>
<thead>
<tr>
<th>a</th>
<th>V at 1 min</th>
<th>V at 2 min</th>
<th>V, 3 min</th>
<th>V, 4 min</th>
<th>V, 5 min</th>
<th>V_{average}</th>
<th>V_{analytical, eq 17}</th>
<th>V_{analytical, eq 16}</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>10.57155</td>
<td>10.58548</td>
<td>10.59788</td>
<td>10.59637</td>
<td>10.58426</td>
<td>10.6</td>
<td>11.5</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Table: Measured voltage ratio at given crack length in specimen 2.

<table>
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<tr>
<th>a</th>
<th>V_{1 \text{ min}}</th>
<th>V_{2 \text{ min}}</th>
<th>V_{3 \text{ min}}</th>
<th>V_{4 \text{ min}}</th>
<th>V_{5 \text{ min}}</th>
<th>V_{average}</th>
<th>V_{analytical, eq 17}</th>
<th>V_{analytical, eq 16}</th>
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<tbody>
<tr>
<td>25</td>
<td>7.14177</td>
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<td>30</td>
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<td>8.44230</td>
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</table>

Table: Measured voltage ratio at given crack length in specimen 3.

<table>
<thead>
<tr>
<th>a</th>
<th>V_{1 \text{ min}}</th>
<th>V_{2 \text{ min}}</th>
<th>V_{3 \text{ min}}</th>
<th>V_{4 \text{ min}}</th>
<th>V_{5 \text{ min}}</th>
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<tr>
<td>20</td>
<td>15.80142</td>
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Table: Measured voltage ratio at given crack length in specimen 4.

<table>
<thead>
<tr>
<th>a</th>
<th>V_{1 \text{ min}}</th>
<th>V_{2 \text{ min}}</th>
<th>V_{3 \text{ min}}</th>
<th>V_{4 \text{ min}}</th>
<th>V_{5 \text{ min}}</th>
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<td>30.3</td>
<td>19.3</td>
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<td>15.36379</td>
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<td>20.8</td>
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<td>22.2</td>
<td>-</td>
</tr>
<tr>
<td>48</td>
<td>23.68520</td>
<td>23.69687</td>
<td>23.66307</td>
<td>23.68037</td>
<td>23.70783</td>
<td>23.7</td>
<td>121</td>
<td>23.7</td>
<td>-</td>
</tr>
</tbody>
</table>
Table: Measured voltage ratio at given crack length in specimen 5.

<table>
<thead>
<tr>
<th>$a$</th>
<th>$V_{1 \text{ min}}$</th>
<th>$V_{2 \text{ min}}$</th>
<th>$V_{3 \text{ min}}$</th>
<th>$V_{4 \text{ min}}$</th>
<th>$V_{5 \text{ min}}$</th>
<th>$V_{\text{average}}$</th>
<th>$V_{\text{analytical, eq 17}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.26553</td>
<td>0.26554</td>
<td>0.26477</td>
<td>0.26423</td>
<td>0.26403</td>
<td>0.265</td>
<td>0.119</td>
</tr>
</tbody>
</table>