A Quasi-DC Potential Drop Measurement System for Material Testing

Joseph Corcoran, Catrin M. Davies, Peter Cawley, and Peter B. Nagy

Abstract—Potential drop (PD) measurements are well established for use in materials testing and are commonly used for crack growth and strain monitoring. Traditionally, the experimenter has a choice between employing direct current (dc) or alternating current (ac), both of which have strengths and limitations. The dc measurements are afflicted by competing spurious dc signals and, therefore, require large measurement currents (tens or hundreds of amperes) to improve the signal-to-noise ratio, which in turn leads to the significant resistive Joule heating. The ac measurements have superior noise performance due to the utilization of phase-sensitive detection and a lower spectral noise density but are subject to the skin effect and are, therefore, not well suited to high-accuracy scientific studies of ferromagnetic materials. In this paper, a quasi-dc monitoring system is presented which uses very low-frequency (0.3–30-Hz) current which combines the positive attributes of both dc and ac while mitigating the negatives. Bespoke equipment has been developed that is capable of low-noise measurements in the demanding quasi-dc regime. A creep crack growth test and fatigue test are used to compare noise performance and measurement power against alternative DCPD equipment. The combination of the quasi-dc methodology and the specially designed electronics yields exceptionally low-noise measurements using typically 100–400 mA; at 400 mA, the quasi-dc system achieves a 13-fold improvement in signal-to-noise ratio compared to a 25-A dc system. The reduction in measurement current from 25 A to 400 mA represents a ~3900-fold reduction in measurement power, effectively eliminating resistive heating and enabling much simpler experimental arrangements.

Index Terms—Cracks, creep, electrical resistance measurement, fatigue, voltage measurement.

I. INTRODUCTION

OVER the last decades, potential drop (PD) methods have become well-established in a number of nondestructive evaluation (NDE) industry applications [1], [2] and ubiquitous in laboratory-based material testing [3]–[9]. The dc or low-frequency ac electric resistance measurements have been used to measure the wall thickness of metal plates, pressure vessels, boilers, tubes, ship hulls, and castings since 1930 [10], [11].

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A natural extension of wall thickness measurement is corrosion and erosion monitoring [12], [13]. This simple technique was first found applicable for crack detection after a surface crack interposed between the electrodes had been claimed to be the reason for anomalous readings during wall thickness testing [1], [14]. PD measurements are now extremely common in laboratory-based crack sizing experiments [3]–[9], [15] and may also be used for strain measurement [16]–[20].

PD measurements are broadly categorized based on the use of alternating (including multifrequency [21], [22]) or direct current (ac and dc, respectively) which have quite different characteristics due to the skin effect [23], [24]. The choice of whether to use ac or dc is primarily determined by the test objectives and the electromagnetic properties of the material under test. The ACPD measurements are well suited to industrial applications of flaw detection, localization, and sizing where measurement accuracy of <5% is sufficient [25]–[28]. However, laboratory-based material tests routinely demand the measurement accuracy of <0.1%. High-precision ACPD systems are certainly capable of this level of accuracy, yet in ferromagnetic materials, the stability is limited by the inherently high variability of magnetic properties. While dc measurements have relatively poor signal-to-noise ratios (SNRs) due to the prevalence of competing spurious dc signals.

It is imperative that PD measurements are as low noise as possible for material testing. Many fracture mechanics analyses are based on the assessment of a rate of change of crack growth, for example, crack growth rate against C parameter for creep crack growth [29] and stress intensity factor, AK, for fatigue [30]. Numerical differentiation amplifies high-frequency random noise [31], and therefore it is imperative that noise is as low as possible so that the noise does not “drown-out” the sought crack growth rate information. Noise performance is also critical for studies concerning damage initiation, which require the identification of small changes in signal.

Recently, a novel quasi-dc approach to material testing has been developed that overcomes many of the issues with the conventional dc or ac techniques. Previous literature [19], [32]–[34] has concentrated on the advances in material testing that are enabled by the technique, while this paper is focused on the technical background of the concept and on the details of the measurement system required for the operation in the demanding transitional regime between dc and ac measurements.

This paper is structured as follows. In Section II, background to the conventional dc and ac measurement techniques will be presented, and the limitations will be highlighted, this is then followed by an introduction to the proposed...
measurements will then be presented and discussed. Section IV
presents the experimental results illustrating the performance
of the system, which is followed by conclusions.

II. AC, DC, AND QUASI-DC POTENTIAL
DROP MEASUREMENTS

All contact PD measurements share similar experimental
arrangements. The measurements require galvanic connection
to the component under test; electrodes are usually spring-
loaded pins (in a deployable, inspection modality) or more
commonly in material testing may be permanently welded
to the surface of the component (facilitating long term and
monitoring type measurements). Typically, measurements are
taken in a four-point arrangement, as illustrated in Fig. 1; here,
the classical example of a compact tension crack growth exper-
iment is used purely as an illustration of one possible mea-
surement arrangement and application. Two electrodes inject
current producing a potential field, while the two voltage-
sensing electrodes are used to measure the potential difference
at remote points on the surface. The relationship between
injected current, \( I \), and measured potential difference, \( \Delta V \),
gives an impedance measurement, \( Z = \Delta V/I = R + iX \),
where \( R \) is the resistance and \( X \) is the reactance (which
equals 0 for dc measurements).

Fundamentally, PD measurements are classified as either
DCPD or ACPD. Clearly, the distinction relates to the fre-
cquency of the injected current, but the behavior of the two
measurements is quite distinct. The choice depends on the
skin effect, which is not present in dc measurements but it
is utilized in ac measurements, as will be explained in the
remainder of this section.

A. Conventional DCPD Measurements

In the absence of the skin effect, the injected current
distribution will be determined by the geometry of the mea-
surement arrangement. In cases where the current injecting
electrode separation is much larger than the thickness of the
component, as shown in Fig. 2(a), the current will be essen-
tially uniformly distributed through the component [Fig. 2(b)].
In cases where the current injecting electrode separation is
much smaller than the component thickness, as shown in
Fig. 2(c), the current penetration will be limited by the
electrode separation [Fig. 2(d)]. In both cases, the resistance
measured from a DCPD measurement may be expressed
simply as

\[
R_{\text{dc}} = \rho \Lambda
\]

where \( R_{\text{dc}} \) is the transfer resistance to be measured, \( \rho \) is
the resistivity, and \( \Lambda \) is a geometric coefficient with units of
inverse length. The presence of a crack between electrodes
will limit the available cross section for current flux and,
therefore, increase the potential difference. The geometric
effect of deformation of the component may have the dual
influence of moving the relative positions of the electrodes
(if they are permanently attached to the component sur-
face) and may also alter the available cross section, both
of which will influence the measured resistance. It should
also be noted that piezoresistivity may influence the electrical
resistivity [32].

DCPD measurements suffer from an unfortunate combina-
tion of smaller signals and a greater noise level relative to
the ac counterpart. It will be explained that the electrical
current penetration of dc measurements is expected to be
much larger than in ac cases; the larger available cross
section means that the measured resistance will be smaller.
In addition, with dc measurements, it is difficult to separate
spurious dc signals arising, for example, from thermoelectric
potentials, stray current, measurement drift (a function of time
[ppm/year]), or instability (usually a function of temperature
[ppm/°C]) though it is possible to largely overcome some of
these issues with more sophisticated techniques such as
polarity flipping [35]. Consequently, the SNR is expected to
be relatively poor. To overcome this, the standard remedy is to
increase the measurement averaging time (to mitigate random
noise) or increase the injected current (to increase the signal).
There is often a limitation to how much averaging is possible,
particularly when measuring time-varying parameters, and
there is a practical limitation to how much current is feasible,
usually dictated by the Joule heating. The relative random
measurement uncertainty is inversely proportional to the mea-
surement current, but unfortunately, the power is proportional
to \( I^2 \). The additional measurement power will need to be
dissipated by the measurement circuit: the cables, contact
resistances, and test component; Table I shows the required
copper cable diameter for a given current. This illustrates
not only the inconvenience of using large current (note that
even larger diameters will be required for cables of higher
resistivity, copper being unsuitable for high-temperature use)
but also the potential to introduce error due to the associated
temperature rise. The resistivity of the test component, and
therefore measured resistance will be a function of tempera-
ture; the component itself may be internally heated by the
current but more critically the cables and particularly contact
resistances will form difficult-to-control “hot-spots”; note that
Table I already assumes the cable temperature has increased
to 60 °C. Reference components are usually utilized to try to
compensate for heating, this approach relies on the assumption
that both the reference component and test component will
have equivalent thermal boundary conditions and will be in
the steady state; the validity of this assumption is not well
established but it makes multiplexing through different current injection locations problematic.

**B. Conventional ACPD Measurements**

In ac measurements, the current is electromagnetically constricted to the surface of the component, restricting the region that is interrogated. The skin effect results in an exponentially decreasing current density with depth. The electromagnetic skin depth, $\delta$, the depth at which the current density is $1/e$ ($\sim 37\%$) of its surface density, is given by the equation

$$\delta = \frac{\rho}{\pi f \mu}$$  \hspace{1cm} (2)

where $\rho$ is the electrical resistivity, $f$ is the current frequency, and $\mu$ is the magnetic permeability of the component. Fig. 3 shows the current distributions for two illustrative cases at a range of frequencies; as the frequency increases, the skin depth decreases, and the current penetration depth becomes constricted to the surface. In ac measurements, the measured resistance (the real part of impedance) is a function of the resistivity, geometry, and also skin depth

$$R_{ac} = \text{Re}(Z) = f(\rho, \Lambda, \delta) = f(\rho, \Lambda, f, \mu).$$  \hspace{1cm} (3)

Usually, it is assumed that the resistivity, measurement frequency, and magnetic permeability are constant throughout the experiment, so changes in resistance are due to geometry. In the presence of a surface, breaking crack the surface constricted current will have a longer path in order to pass around the defect; concentrating current to the component surface usually leads to enhanced sensitivity to surface cracks.

The SNR of an ac measurement is usually much better than the dc equivalent. First, as the current is constricted to the surface, the current carrying cross section is effectively reduced, so increasing the resistance (and hence PD “signal”), and second, the noise is reduced. Phase-sensitive detection using a lock-in amplifier enables the isolation of signals at a specific frequency and phase; in this way, very small signals can be measured accurately even in the presence of much larger amplitude noise. At increasing frequencies, we move away from spurious dc-like thermolectric or stray potentials, and additionally, the random noise is reduced, as will be discussed in more detail in Section III.

Unfortunately, the limitation with ac measurements is the assumption that the skin depth determining magnetic permeability is constant. In ferromagnetic materials, the magnetic permeability is known to vary substantially as a complex function of many different factors including temperature, microstructure, stress, and magnetic history [38]. The result is that in a wide range of materials of significant engineering interest, the magnetic permeability and, therefore, skin depth are likely to vary significantly, causing spurious undesired resistance changes; ac measurements will, therefore, be unsuitable for high-accuracy material tests in ferromagnetic materials.

**C. Quasi-DC Potential Difference Measurements**

The previous section highlighted the unfortunate compromise for those wishing to use PD measurements for materials testing. While ac measurements offer good SNR, they are not well suited to material tests of many materials. On the other hand, dc measurements, where the skin effect is not present, may require very significant measurement power to
obtain adequate SNR, which is not only practically difficult but also may risk instability through the Joule heating. This paper proposes a very low frequency, quasi-dc measurement that combines the advantages of both ac and dc measurements.

Fig. 3 shows that it is possible to observe that when the measurement frequency is reduced sufficiently, the current distribution tends toward that of the dc distribution. At low frequencies, the skin depth may become sufficiently large that the penetration depth is no longer limited by the skin effect but rather geometry, either the component thickness or the electrode separation, just as with dc. The frequency where this transition occurs may be calculated from (3) as [33]

\[
f_T = \frac{\rho}{a^2 \pi \mu}
\]

where \(a\) is the penetration limiting dimension. Fig. 4 illustrates that both the magnitude and phase of the measured impedance

Fig. 3. Finite-element simulation results obtained using COMSOL Multiphysics [37], simulation results also discussed in [33]. Current distributions in a 100 mm × 100 mm × 20 mm block with the relative magnetic permeability of 1 and the conductivity of 100% IACS. (a) Current injected at opposite ends of the component. (b) Current injected between two points separated by 10 mm on the surface of the component. i) Illustration of the two cases. ii)–v) Streamlines show the current path for a range of frequencies. vi) Current density is plotted as a function of distance from the top face of component. The current density is normalized to its maximum (on the surface at the highest inspection frequency).
The improved SNR means that the inspection interest, resulting in greatly improved SNR compared to the lock-in. Multiplexers may be used to switch through a range of injection and sensing locations.

As quasi-dc is in fact still ac (albeit very low frequency), it is still possible to benefit from phase sensitive detection. Lock-in amplifiers can be used to isolate the frequency of interest, resulting in greatly improved SNR compared to the dc alternative. The improved SNR means that the inspection current can be greatly reduced to a point where the Joule heating becomes negligible; recall that the heating power is proportional to the square of the injected current. The use of quasi-dc, therefore, results in a dc-like measurement that can even be used in cases where permeability variations limit the use of the conventional ACPD, with the SNR performance of an ac measurement, permitting low noise very low-power measurements.

Table II provides a summary of different approaches, showing the quasi-dc technique combines desirable attributes of both dc and ac techniques.

III. INSTRUMENTATION FOR QUASI-DC POTENTIAL DROP MEASUREMENTS

Section II described the motivation for using very low frequency and quasi-dc measurements. Quasi-dc measurements are relatively uncommon and when combined with the strict requirements demanded in material testing, a unique set of requirements results. A measurement system must have the following.

1) Operate down to the megahertz range.
2) Be capable of measuring micro-ohm resistances.
3) Have excellent noise performance.
4) Have excellent magnitude and phase stability.
5) Measure small transfer resistances as low as 10 μΩ in the presence of source resistances as high as 10 Ω (constituting the measurement circuit of cables, connections, and test component).

A bespoke measurement system has been developed to fulfill these requirements [40] and is presented in this section. Fig. 5 shows a schematic of the system, illustrating its operation. A digital lock-in amplifier is at the heart of the system; the output and returned signals are processed with a phase sensitive lock-in algorithm to calculate the magnitude and phase of the impedance. The waveform generator of the lock-in amplifier produces a fixed frequency sinusoid, which is then boosted into a fixed amplitude differential current at the current driver; the current is used to interrogate the specimen. The resulting potential difference across the test component is then amplified and shaped by a preamplifier and an amplifier that is integrated with the voltage sensing side of the lock-in. Multiplexers may be used to switch through a range of injection and sensing locations.

The performance is dependent on the whole system; the drift and stability will be limited by the “weakest link.” The noise performance of the system is predominantly determined by the first amplification stage, the preamplifier, and therefore, this is where the remainder of this section will be focused.

The primary issue associated with low-frequency measurements is “flicker” noise, random noise with a 1/f power density spectrum; the noise density, therefore, increases with lower frequencies. (The interested reader is directed to the work of Lenoir [41] for an analysis of measurement variance as frequency tends to dc.) Flicker noise presents a compromise for quasi-dc measurements; the measurement frequency must be sufficiently low so that the skin effect is suppressed but should also be as high as possible to reduce the noise density. In order for measurements to be feasible in the quasi-dc regime, it is imperative that the preamplifier has extremely low-noise performance. Fig. 6 shows the voltage noise density of a very good “low-noise” commercial preamplifier [42], compared to three preamplifier options with increasing noise performance available for the quasi-dc system.

The excellent noise performance is achieved by first using contemporary low-noise amplifier components and circuit design, and subsequently, improvements are achieved by simply adding further preamplifiers in parallel [43]. The input noise voltage decreases in proportion to the square root of the number of parallel amplifiers but the input noise current...
TABLE II

SUMMARY OF THE DIRECT AND ALTERNATING PD TECHNIQUES. GREEN DENOTES POSITIVE ATTRIBUTES, WHILE RED DENOTES NEGATIVE ATTRIBUTES

| Direct PD | Quasi-DC PD | Alternating PD |
|-----------|-------------|----------------|
| Not subject to the skin effect | Not influenced by the skin effect – provided sufficiently low frequency | Subject to the skin effect |
| High noise (spurious signals and phase sensitive detection not possible) | Low noise | Very low noise |
| High current (10’s or 100’s of amps) to provide sufficient signal to noise ratio. | Typically 0.1-1 A | Typically 0.1-1 A |
| Requires large cables or busbar connections | Thin, low conductivity wires are possible | Thin, low conductivity wires are possible |
| Risk of significant Joule heating | Negligible Joule heating | Negligible Joule heating |

Fig. 5. Schematic illustrating the quasi-dc measurement system.

Increases by the same factor; however, since the source impedance is very low in PD measurements (<10 Ω), the effect of increasing input noise current has no significant effect on the measurement system performance. The use of these specially designed low-noise preamplifiers enables accurate measurements at increasingly low frequencies.

It should be noted that SR560 used for comparison is not intended for use with the very low source resistances common in PD measurements. Transformer coupled preamplifiers (e.g., SR554 [44]) are more suitable for low source impedances, but due to the inherent ac operation, they introduce a high-pass filter transfer function; as an example, at 10-Ω source resistance, SR554 exhibits a cutoff frequency of approximately 5 Hz, below which the signal magnitude drops and a significant phase shift occurs. The high-pass filter has poor stability, particularly if the transformer becomes magnetized, making them unsuitable for quasi-dc measurements.

Confidence in measurements may be achieved through either longer averaging times or increasing the measurement current. The increase in noise density at lower frequencies also adds choice of measurement frequency into that decision; clearly, at a lower frequency, higher noise measurement will require more current or averaging to achieve a comparable measurement certainty. Referring back to Fig. 6, the noise density of the 4× preamplifier increases from 0.30 nV/√Hz at 10 Hz to 0.66 nV/√Hz at 1 Hz; to gain equivalent certainty at the lower frequency, higher noise point the averaging time would have to be increased roughly 4.8-fold or measurement current increased 2.2-fold.

The resulting performance of the quasi-dc measurement system enables low-power measurements at currents of typically 100–400-mA rms. The low-power measurements result in negligible Joule heating so that measurements are not influenced by the associated increase in temperature. Implementing measurements are simpler when using lower currents, especially at high temperature, as thick copper (or other precious metal) cables are not required. Multiplexing through a number of injection locations is straightforward; simple low current capacity relays can be used, and there is no need to wait for the Joule heating to become a steady state. The low-power PD measurements are well suited to field use and could potentially be battery powered.

IV. EXPERIMENTAL DEMONSTRATION OF A QUASI-DC POTENTIAL DIFFERENCE MEASUREMENT SYSTEM

The motivation for using quasi-dc frequencies for material testing has been provided, in addition to a description of the instrumentation that has been developed. This section illustrates through four example experiments key features of using quasi-dc frequencies. In the first, suppression of the skin effect is demonstrated, and in the second, the noise performance and measurement power are compared against conventional dc techniques, while the third and fourth compare performance in two typical tests in which PD measurements are used, creep crack growth and fatigue experiment.

A. Suppression of the Skin Effect

One of the premises for utilizing quasi-dc measurements is that changes in magnetic permeability in ferromagnetic
materials undermine the stability of ac measurements so that they are not suitable for high-accuracy laboratory tests. Magnetic permeability is known to be strongly dependent on many different variables, particularly stress [38], which may change through the duration of a material test. To illustrate the importance of using sufficiently low (quasi-dc) frequencies, a PD experiment was conducted on a mild steel test specimen exposed to a range of applied loads.

A square configuration of electrodes was welded to the surface of a tensile test specimen, as illustrated in Fig. 7. This measurement configuration is relatively arbitrary as similar behavior will be present with different electrode configurations in ferromagnetic materials; the square arrangement is utilized for creep strain measurements [19], [34]. The test component was formed from S275 steel with cross section of 75 mm × 24 mm. Measurements were taken at a range of frequencies from 0.3 to 60 Hz (the mains frequency was 50 Hz) with a measurement current of 300 mA. Applied loads ranging from −100 to 400 kN (equating to −16.5%–66% of the yield stress) were applied in steps.

Fig. 8 shows the resistance measurements for a selection of frequencies as the applied stress is varied. The measurements show that at low frequencies, the measured resistances are insensitive to the applied load; as the skin depth is large (greater than the electrode separation), the penetration depth is limited by geometry as opposed to the skin effect, and the measurements are, therefore, insensitive to the spurious changes in the magnetic permeability. As the frequency is increased, the skin depth is reduced; consequently, the current penetration is increasingly controlled by the skin effect, and therefore the measurements become increasingly sensitive to the changes in magnetic permeability that come with applied stress. Fig. 8 illustrates the peril of using ac measurements in ferromagnetic materials; spurious changes in the magnetic permeability can have dramatic undesired influence on measurements.

The influence of the skin effect may be seen more clearly with a plot of resistance against frequency, as shown in Fig. 8(b). At the lower frequencies, the resistance measurements can be seen to tend toward a “dc-asymptote”; the measurements in this regime behave as dc measurements and are referred to as quasi-dc. At higher frequencies, the skin effect becomes more significant and the measurements become increasingly sensitive to the changes in the magnetic permeability that comes with an elastic load. Clearly, at higher frequencies, the spurious changes in resistance resulting from changes in the magnetic permeability will mask the sought resistance changes arising from geometry. Measurements must be taken in the quasi-dc regime so that the influence of the skin effect is adequately suppressed; it should be noted that many commercial ACPD measurement systems are not capable of measurements in the very low-frequency (<10 Hz) range.

Interested readers are referred to [45] for more information on the influence of elastic stresses on PD measurements.

It is worth re-emphasizing the compromise in the selection of the measurement frequency. The measurements must be sufficiently low frequency so that the skin effect is suppressed but equally should be as high as possible so that the flicker noise is reduced. It is suggested that the random error that results from flicker noise is preferential to the systematic error that may result from susceptibility to the skin effect as the random error may be reduced by time averaging or increasing the measurement power. A prudent strategy is to reduce the measurement frequency only so far that the potential influence of the skin effect is reduced safely within satisfactory bounds, and then time average or increase measurement power as necessary to obtain the required measurement accuracy. It may be necessary to take measurements in the “transition region”...
between quasi-dc and ac measurements, for example, if the transition frequency is exceptionally low due to large dimensions of the components, in which case the skin effect compensation strategy described in [33] is suggested.

B. Enhanced Noise Performance and Low-Power Operation

The quasi-dc technique and measurement system have been developed with the aim of achieving improved SNR while also using far lower amplitude inspection current than conventionally used in dc measurements. A comparison has been arranged between the quasi-dc system described in Section III, a conventional dc measurement, and a more sophisticated commercial dc system.

A similar measurement arrangement to that described in Section IV-A, as shown in Fig. 7; a square configuration of electrodes was welded to an S275 steel component though this time the electrode separation was 10 mm and the component dimensions were 25 mm $\times$ 100 mm $\times$ 100 mm; the resulting transfer resistance is approximately 2 $\mu$Ω. This is an equivalent measurement arrangement to that proposed for creep strain measurement in [19] and [34], though on this occasion measurements will be taken on a room temperature, unloaded component for ease of comparison.

The dc system is composed of a dc power supply (TDK-Lambda, ZUP10-80 [46]) with a 6½ digit digital multimeter (National Instruments, NI-USB 4065). The more advanced specialized system (Matelect, DCM-2 [47]) is capable of “pulsed DCPD”; instead of a continuous dc current, the current is switched ON and OFF at given intervals so that measurements can be taken relative to the off periods to effectively eliminate spurious dc signals, most notably thermoelectric potentials. The DCM-2 also offers dedicated preamplifiers and a parallel measurement channel for simultaneous measurements of a “dummy” reference component, again an attempt to reduce systematic uncertainty on the assumption that the two components will be equally influenced by the Joule heating. For a full list of specifications for DCM-2 (see [47]).

Fig. 9 shows the data comparing different measurement systems. Measurements were taken over an hour, each data point being averaged over 25 s. It is important to note that the direct comparison is relatively arbitrary as a different measurement current amplitude was chosen. The dc system used a continuous 5 A, the Matelect system used 5 A with a 50% duty cycle, while the quasi-dc system used a 400-mA rms sinusoidal current; the dc system and Matelect dc system,
Fig. 9. Time trace showing the typical noise performance of three potential difference measurement systems. Each data point is averaged over 25 s. A 10-mm square configuration of electrodes welded to an S275 steel component of 100 mm × 100 mm × 25 mm; the nominal transfer resistance is approximately 2 μΩ. (This is a relatively low resistance, and therefore the random uncertainty is large.) Points are joined to aid visibility.

As previously mentioned, the standard means of reducing the random uncertainty in a measurement is to increase the measurement power. Fig. 10 shows how the relative standard error of the dc measurement is reduced by increasing the measurement power; the measurement standard error is inversely proportional to the current and, therefore, the square root of the measurement power. Unfortunately, it can be seen that beyond 25 A (∼3900× the measurement power of the 400-mA measurement), the standard error of the measurement begins to increase; this is a consequence of the excessive Joule heating of the 0.8-mm-diameter copper cables and contact resistance with the test component; the cables failed at 35 A. The experiment shows the limitation of relying on increasing current to reduce measurement uncertainty; there are diminishing returns in increasing the current, and so the increase in measurement power may need to be very substantial, and eventually there will be a practical limit to how much current can be injected. As an example, comparison of the performance, the 400-mA quasi-dc measurement uses ∼3900 times less measurement power than the 25-A conventional dc measurement, yet still achieves a 12.9-fold improvement in SNR (defined here as the standard deviation of normalized resistance measurement). The improved noise performance enables the improved insight into the fracture mechanics.

To illustrate the issue of the resistive Joule heating further, infrared thermography was used to visualize the temperature increase in an example experiment. A 316H stainless steel compact tension component (which will be used for the creep crack growth experiment in the following section) was prepared with current injection electrodes, as illustrated in Fig. 1; the width of the component was 25 mm, length 62 mm,
Fig. 10. Standard deviation against measurement power for the measurements shown in Fig. 9; both standard deviation and measurement power are normalized to the quasi-dc measurement. A range of dc amplitudes was used to illustrate the inverse proportionality between measurement standard deviation and square root of measurement power until the Joule heating begins to influence the measurement.

Fig. 11. Infrared thermography images of a 316 stainless steel component subjected to increasing levels of dc current. The whole assembly was sprayed matt black and emissivity assumed to be 0.95.

and initial crack length 12 mm. In this case, the current carrying cables were 1 mm × 12 mm brass bars, which were then fixed to M3 threaded stainless steel studs welded onto the component.

Fig. 11 shows a summary of the images, illustrating the temperature increase. Current at 300 mA (typical of the quasi-dc), technique causes a negligible increase in temperature. As the current increases, the temperature of the component and electrical cables can be seen to increase; notably, the electrical connection to the component appears as a hotspot due to the relatively high serial resistance. At 40 A, the bulk material temperature increases to 10 °C above ambient, while the connection temperature is over 25 °C above ambient; the temperature increase will be dependent on the thermodynamics
of the situation at hand and will, therefore, be sensitive to changes in boundary conditions. The increase in temperature will cause an increase in resistivity, so the measurements will be reliant on the stability of the thermal boundary conditions.

Evidently, radically different approaches of using quasi-dc measurements together with the measurement system designed for this purpose offer extremely low-noise measurements, permitting very low-power measurements, which for materials testing purposes have the negligible Joule heating. The low-power measurements also enable much greater flexibility in the execution of measurements; large diameter and high conductivity cables are not required.

C. Example Creep Crack Growth Experiment

A creep crack growth experiment was carried out in order to demonstrate the advantages of the quasi-dc measurement
system in a real experiment; a four-fold preamplifier, 400-mA measurement system is compared against a standard 20-A dc system (a measurement power difference of ×2500). Both quasi-dc and dc measurements were conducted simultaneously as they will not interfere with each other. The 316 stainless steel compact tension component previously shown in Fig. 1 was used. In the experiment, the 20-A dc current used the 1 mm × 12 mm cross section brass busbar connections clamped to the component, while the 400-mA quasi-dc current used 0.8-mm-diameter nichrome wires (thermocouple wires, identical to the potential sensing wires) which could be easily spot-welded in place.

The results of the experiment are shown in Fig. 12. Despite the orders of magnitude smaller measurement current, the accuracy of the quasi-dc measurement is clearly vastly superior. These improved results are particularly critical.
in studies where identifying damage initiation is required (see [48] for work on creep crack initiation using a quasi-dc technique) or where rates of change need to be calculated (e.g., in C-w-based analysis [29]). Fig. 12(c) shows that the rate of change can be measured far more accurately with the quasi-dc technique due to the lower noise. This means that rates of change can be measured reliably much earlier, when the rate is lower. In addition, the ability to use thin wire connections makes the execution of the experiment much simpler, particularly at high temperature.

D. Example Fatigue Experiment

An exactly equivalent component and measurement arrangement as the creep crack growth test was utilized for a room temperature fatigue test. Cyclic loads of 1.1–11 kN (stress ratio, \( R = 0.1 \)) were applied at 7 Hz. The results of the fatigue experiment are shown in Fig. 13. Again, the noise performance of the quasi-dc measurements is far superior to the dc measurement, despite using 2500 times less measurement power. The reduction in measurement power effectively eliminates the measurement, despite using 2500 times less measurement power.

The data shown in Fig. 13 have a nominal resistance of 70 \( \mu \Omega \) with a standard deviation of 2.8m\( \Omega \) (averaging time 15 s). The standard deviation in normalized resistance is, therefore, 0.004%. In order to calculate the standard deviation in the crack size estimate, a calibration function was determined using COMSOL Multiphysics [37] following ASTM E647 [49]; the resulting standard deviation in crack size is 0.83 \( \mu \)m. It should be stressed that these values are greatly dependent on the exact situation and this relatively large specimen is a demanding case; a greater baseline resistance will yield proportionally lower variance in the normalized resistance. The crack size standard deviation is additionally dependent on the calibration function; in general, components that are smaller in scale will have much improved crack size accuracy. Moreover, it should be stressed that the standard deviation does not determine the resolution as the averaging time can be increased to yield improved measurement confidence.

Fatigue analyses frequently require assessment of crack growth rate, particularly in Paris law analysis. Fig. 13(c) shows the rate of change of resistance using a 15-point running linear regression, comparing the low-noise quasi-dc measurement and the conventional dc technique. The improvement in noise performance leads to a transformational improvement in the quality of the rate of change measurement. The improved noise performance is also critical for identifying crack initiation.

V. Conclusion

PD measurements are attractive for materials testing due to their simplicity and robust hardware suitable for harsh environments and high temperatures. A quasi-dc technique is suggested, combining desirable attributes of both ac and dc PD techniques. At sufficiently low frequency, the skin effect is suppressed and, therefore, measurements behave effectively as dc; quasi-dc measurements are, therefore, nominally insensitive to magnetic permeability and are stable in ferromagnetic materials. Phase-sensitive detection enables the isolation of signals at specific measurement frequencies; the use of higher frequencies reduces the spectral noise density, so greatly improving the SNR of measurements. A measurement system has been specially designed for use in the demanding quasi-dc regime and is well suited to the low source impedances typical of PD measurements.

The combination of the quasi-dc approach and the bespoke measurement system delivers superior noise performance at lower amplitude inspection current that the dc alternative. The low-power measurements are advantageous for many material testing applications as they effectively eliminate the influence of the Joule heating, simplify electrical connections, and facilitate multiplexing. Improved noise performance is critical for improved insight into material behavior, particularly when establishing the rates of change or detecting the damage initiation.

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