Current progress in the use of potential drop for condition monitoring of creep in high temperature/pressure industrial plant.

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Abstract

Electrical potential drop is a well-established method for laboratory crack growth measurement and in-field NDT. We describe here the application of the two separate variants of EPD (ACPD and DCPD) to monitor the progress of creep damage in pressure vessel materials and components, in an on-line continuous monitoring context. ACPD and DCPD have been employed by the authors in a long-term programme, over 4 years, carried out on a range of specimens and vessels. The results have been very encouraging and have consistently revealed an ability to detect creep damage many months before final failure occurs, and to stop long-term tests ahead of final fracture/failure, when close to a component's end-of-life. A variety of EPD responses have been seen in tests, making data interpretation challenging, but not impossible. EPD readings can be influenced by a variety of phenomenon, many unrelated to creep damage, so it has been necessary to develop an approach based on a "signature" of EPD data from multiple monitored locations on a particular test piece. The combination of AC with DCPD has helped deconvolute the various unrelated phenomena from that due to creep damage (which is sometimes much more subtle). We report on the methods employed, plus the practicalities of physically connecting to plant in the field, ways of ensuring long term connection efficacy and reliability, and the benefits of the combined AC/DC instrumental approach. We speculate on the possible extension of our methods to other time-dependent degradation mechanisms in industrial plant, such as HTHA and HE. The overall methodology holds great promise for condition monitoring of power-plants, pipelines and their end-of-life prediction.

1. Introduction & background

The electrical potential drop (EPD) an established technique, with a long history of use for the measurement of crack initiation/growth in metals. EPD (also known simply as Potential Drop, PD) remains a powerful way to gauge crack size (principally depth, but also surface breaking width and even inclination) in a variety of contexts, including laboratory-based fracture/fatigue testing[(1)], in-field NDE, and on-line continuous monitoring. Modern EPD equipment offers high resolution (often to microns of crack growth), via advanced electronics providing noise reduction, and multichannel capability, within a compact, expandable, fully digital system.

EPD relies upon the passage of an electrical current (usually maintained constant) through a conductive test piece, and the subsequent measurement of the potential drop developed in order to pass that current. Accordingly there is an AC variant (ACPD) and a DC variant (DCPD). The latter was developed over 50 years ago, whereas the former is a more modern development, dating from the 1980's [(2)]. ACPD differs from its DCPD cousin in so far as the current flow through the specimen is not normally regraded as uniform, and is also a strong function of the frequency of the AC applied. Alternating currents are expected to be surface "hugging" (the so-called skin effect) whereas direct currents can largely be assumed to flow uniformly through the bulk metal.

EPD methodology is so well established that it's use in fatigue and fracture toughness determination is recognized by several internationally applied standards (e.g. ASTM647 and 1820 [(3,4)], however no such regularisation exists for creep crack growth studies. The use of EPD to monitor creep is not new, however, and relies upon the fact that many of the factors associated with creep in metals, such as the development of plastic strain, the formation of cavities - and their eventual coalescence to generate demonstrable crack-like defects, affect, or are expected to influence, the EPD signals in much the same way that a developing crack would. However EPD usually comes into its own when most of the creep lifetime of the metal has been expended, and definite cracks have developed.

Both variants respond well to surface breaking defects, with DCPD also showing some sensitivity (in theory) to bulk defects such as internal cracks. The literature available on the use of EPD to detect the early stages of creep damage – the so-called incipient damage stage (such as cavitation) - is not comprehensive, which is not entirely surprising given the likely nuanced changes in electrical properties that could occur. Cavitation begins with the development of defects that are of nanometre dimension [(5)] and even if these are prolific in number, very small changes in resistivity (which could in turn affect the measured DC and ACPD) are predicted. Recent modelling [(6)] has shown that the expected changes in DCPD likely as a result of cavitation (modelled principally from a geometric viewpoint) are far below the changes in EPD measured in practice, suggesting that either the modelling is flawed on that incipient damage is not simply a case of cavitation development – and that the DCPD is responding to other, as yet unidentified, changes at the microstructural level, for example microcracking or localized strains.

In order to be able to detect such nuanced changes in EPD response, the experience of the authors [(7)] has shown it necessary to deploy EPD in a continuous monitoring mode - much like it would be applied in a laboratory fatigue crack growth study. This is in marked contrast to the use of EPD in a "spot-checking" (i.e. interrupted or intermittent) mode, as has been more common when it has been deployed in the field as an NDT technique to assess creep damage at outages of plant. That this has been found to be the case is not surprising given the small signal changes experienced, and the "noise" observed in measurements inherent with intermittent deployment. Spot checking normally requires a hand-held probe that is used to apply all four electrical contacts to the specimen (see later) and the uncertainty in positioning, and possible changes in surface oxidation and even roughness between readings will easily swamp any subtle changes in EPD. Additionally the influence of other differences in the state of the test piece, such as the load or strain that it is under, and its operating temperature, have been observed to generate changes in EPD that can be orders of magnitude above that due to incipient damage. In other words, it is necessary to look at all the data over a much longer period, and how it develops over time, before being able to see the fine detail commensurate with incipient damage.

Recent studies by the authors have focussed on the use of a combination of AC and DC EPD to help detect the predicted (and now observed) nuanced changes in EPD signal magnitudes during the early stages of creep. As will be seen in this present publication, this combination of the two variants was initially attempted because of the uncertainty in predicting which variant would be the most sensitive to incipient damage, taking into account the pragmatic view that the opportunities for undertaking long term creep tests on life-size specimens at high temperature and pressure are both expensive to initiate and run, and likely to be prolonged in duration – so necessitating a "one-shot" approach. This combination of methodologies was not without its challenges (as will be recounted below) but nevertheless proved an inspired decision, as the results have appeared to indicate that a synergistic benefit exists when deploying both variants together. This is further discussed below (and elsewhere (7)) but in essence amounts to the observation of a series of trends in the AC and DC EPD responses, that when considered together, constitute a "signature" response that helps identify incipient damage and differentiate this from the final stages of creep failure.

In addition to the science, much effort has been expended on getting the engineering into a state where laboratory based EPD methodologies and equipment can be transferred into the less than conducive industrial context inherent within the main beneficiary of this technology – the powergen sector. There is little point in developing methods to detect incipient damage, and follow its progress remotely, if these cannot be easily applied into non-laboratory contexts. Speed of installation and reliability of the electrical connections to the test piece are paramount in this sector – with the window for getting kit installed and operational usually being a matter of a few days rather than weeks, when plant has moved to an "outage". Long term reliability is clearly critical, given the temporal periods between plant outages. The majority of the practical issues have now been overcome, but there will still be lessons to be learned.

The one remaining barrier to the use of EPD in an industrial continuous or condition monitoring context remains the need to interpret the signals emanating from an operational installation. As will be seen below, EPD signals can change at alarming rates, but few of these changes are likely to be associated with rapid crack growth and imminent failure. Clearly some interpretation needs to be made of the signal changes observed, and it is recognized that if this barrier is to be overcome, a certain "de-skilling" of the interpretation phase is required. On a positive note, the existence and observation of the EPD signature, already cited, and further discussed below, will make this interpretation far easier – and may even allow it to be automated by the use of appropriate software algorithms, and work is in hand to achieve this end.

This paper summarises the work done to date in using EPD to detect incipient damage in semi-industrial testing contexts, describes the technology, outlines the results already obtained, and provides some critical appraisal for the full implementation of AC/DC EPD into an industrial context such as a power station.

2. Experimental work

In its most basic form, EPD relies upon a measurement of a specimen's electrical impedance. In the case of DCPD, this is specifically the electrical resistance, whereas in ACPD, capacitive and inductive components complement the electrical resistance to generate a more complex interaction(8). Impedance is normally measured using a four-point arrangement of in-line electrical contacts, with the outer two connections delivering the excitation current, and the inner two allowing measurement of the potential drop (the "EPD") required to drive the excitation current through the specimen. The method relies upon the influence of a defect on the specimen's impedance. Normally the presence of defects such as cracks raise the local impedance, and therefore can be detected by a rise in the local EPD. Measurements are normally simplified by ensuring that the excitation current is known and remains constant at least throughout the duration of the measurement. As mentioned earlier, a further subtlety of ACPD over DCPD is the existence of the so-called skin effect, where the excitation current is found to travel close to the surface of the specimen, rather than uniformly throughout its cross-section (the latter being largely the case for DCPD). A practical consequence of this phenomenon is that the calibration methodology (EPD vs crack depth) is different for ACPD compared to DCPD. Additionally the depth that most of the current penetrates to (the skin depth) is a function of the frequency of the AC excitation, and this provides ACPD with an extra degree of freedom which can both add information or complicate interpretation (depending on one's viewpoint!). The higher the frequency, the smaller the skin depth, and the more sensitive the technique is to surface breaking defects.

EPD excels at providing a continuous electrical response that is proportional to crack dimensions and as such it is often the only crack monitoring technique that can be used in extreme testing contexts such as at high temperatures (e.g. thermomechanical testing of superalloys)(9), under corrosive atmospheres (e.g. H_2S induced cracking in the oil and gas industry, or stress corrosion cracking of stainless steels under high pressure high temperature aqueous conditions)(10), or even in high radiation environments (such as in-pile testing of materials in the nuclear industry). In such contexts, EPD is normally used in a continuous (on-line) sense to monitor for crack initiation and crack growth.

Aside from cracking, EPD can respond to a range of other effects that might be of interest including microstructural differences (such as within welds, or after case hardening), internal defects (e.g. porosity), residual stress measurements (ACPD is very sensitive to the level of elastic and plastic strain in ferrous materials), and the early stages of creep damage development, such as the formation of cavities. EPD may also offer an insight in other mechanism that would be expected to alter resistivity or impedance – such as hydrogen embrittlement (see later).

Many of the practical challenges associated with EPD relate to the engineering difficulties in the way in which electrical connections are made to specimens[7], and continuous monitoring in an industrial context poses additional difficulties associated with installation, such as access, the provision of power and external communication channels, as well as tight installation deadlines during plant outages.

For NDT applications, EPD equipment can be battery powered and then used for spot-checking of cracks in structures (particularly ACPD, given its better portability), with the 4-point connections being made by some kind of re-position-able or hand-held “probe” head which usually houses sprung loaded pins able to penetrate surface oxides or contamination. However, resolutions reached (in terms of crack depth) are nothing like that achievable in an on-line context, mainly due to variabilities experienced in making reliable connections (and in locating the same measurement location after typical outage intervals have passed). Furthermore, hand-held spot checking is far more suited to ACPD than DCPD – simply because the excitation currents required when using DCPD are often far too high for the sprung contacts employed. Currents have to be in the 10’s of amps before a decent measurable DCPD can be obtained, depending on specimen sizes. Typical currents in ACPD studies are an order of magnitude less, but hand-held ACPD probes are very susceptible to registering changes in signal magnitude due to differences in approach angle and contact pressure. These effects are linked to the existence of a variable error signal, known as “pick-up” that superimposes upon the specimen-derived signal. Overall, such effects generally limit handheld EPD to a resolution of no better than 0.5mm in crack depth measurements – significantly different from the 10 micron resolution that is normally achievable for typical cracks in a continuously monitored situation[7]. Using spot checking is therefore far from ideal, but has often been the methodology employed by plant operators and inspection companies, often leading to disappointment in the efficacy of EPD methods.

In contrast to spot-checking, the application of EPD to long-term monitoring will suffer none of the issues described above. However, other than its highly common use in the laboratory as a means of measuring long term fatigue crack growth, EPD seems to have been rarely used for on-line use, and this may have something to do with the practicalities of making robust connections in the field as well as interpreting the data generated. In 2015, the authors embarked on a long-term study of using EPD to detect and monitor creep damage in P91 and P92 steel pressure vessels undergoing laboratory testing. In this study, many of the practical issues associated with specimen connection and apparatus deployment were overcome. To date, data interpretation remains an on-going challenge although, as will be described here, all the signs are that a path going forward has been identified, with the main need being the acquisition of more data and installation experience to build up a database of EPD responses across different specimen geometries, environments and contexts.

Part of the advance made by the authors has been to combine the AC and DC variants of into one monitoring system to effectively create a "AC/DC"-EPD set-up [7]. This has enabled the benefits and strengths of both variants to be captured in one on-line test, and has also revealed a synergistic effect which appears to greatly enhance an operator's ability to determine (in this case) how close to end-of-life a monitored component is. We further describe this below when discussing the results of work already completed.

The AC/DC set-up employed required the interfacing of two commercial EPD instruments together, one providing ACPD capability and the other, DCPD, (Matelect Ltd, London). This was achieved by using a series of signal and current multiplexing (switching) units which also facilitated connection to multiple points on the test vessel. Several cylindrical pressure vessels were monitored, in the three-year study. Figure 1 shows one of these - manufactured from P91 steel and containing two circumferential welds. The vessel was loaded axially and was also subjected to both elevated temperature (ca 700 ^{o}C), and an internal pressure. Failure was expected to initiate in the HAZ of the welds by Type IV cracking at around 10k hours, and it was these zones that were monitored by the EPD system. Scheduled outages occurred so that other off-line NDT characterisation methods could be employed, including ACPD in a hand-held mode.

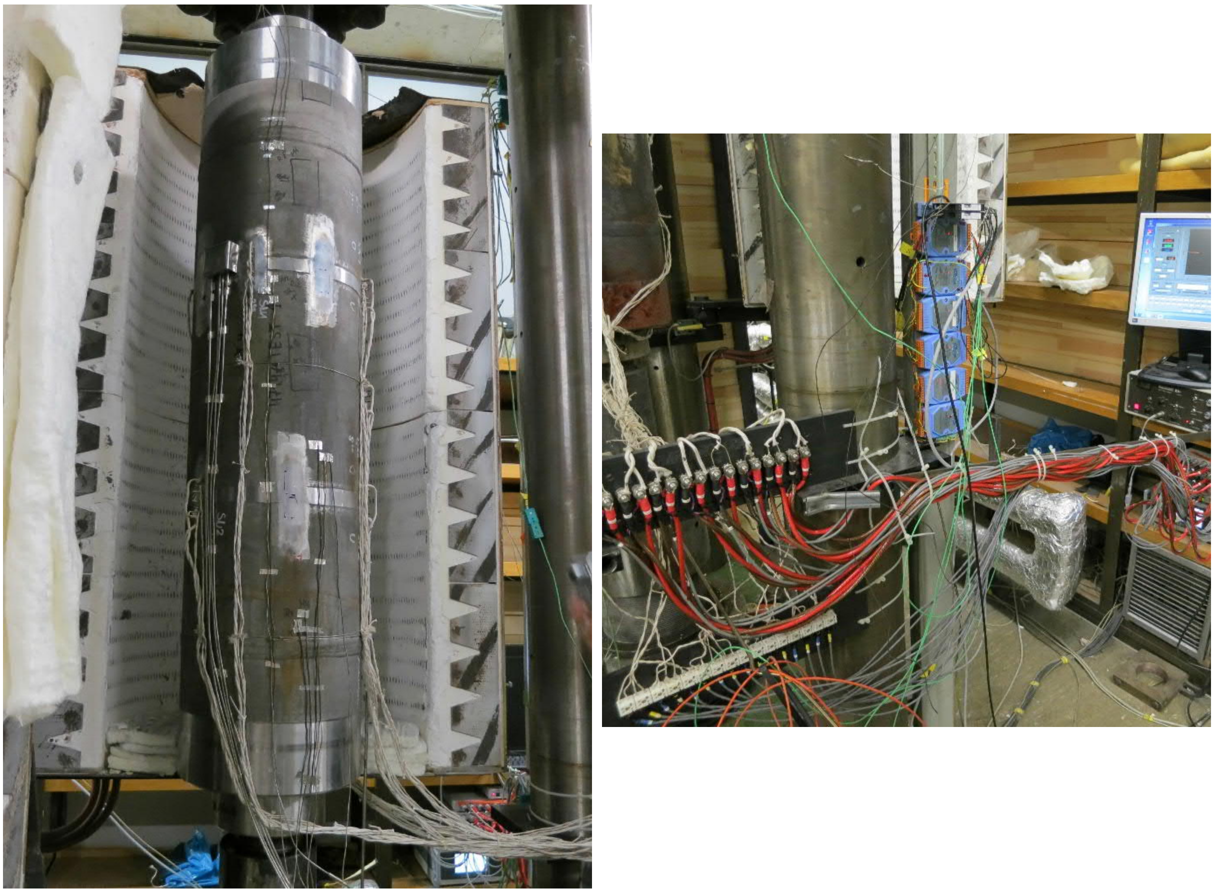

Figure 1. Left - pressure vessel in open split-furnace, just after EPD connections have been completed, Right - routing and conversion of HT wiring to RT cabling

The deployment of both EPD variants was initially pragmatic, as the authors were not clear on which of the methods would offer the best solution, largely in terms of practicality, reliability, and (significantly) in response to incipient damage and the ability to resolve any changes in signals. Part of the problem is the fundamentally different ways in which alternating and direct currents flow in a conductive material and also interact with a material's physical, electrical, and magnetic properties. Accordingly, a significant feature of the AC/DC system was the ability to employ only one set of electrical connections for both EPD variants. This both simplified connections and reduced the number of wires and connection points to the test vessels, the only disadvantage being that the ACPD current carrying wires were, in effect, much thicker than they would normally be (given they also had to be capable of carrying the higher direct currents for DCPD).

After much trial and error, a connection methodology which involved the use of stainless steel studs (ca. 20mm long x 2mm diameter) silver-soldered to pure silver wire, the whole being sheathed in silica braiding, was eventually employed. The studs were originally welded to the vessels using a conventional spot welder, and the wire silver-soldered in-situ. Specific engineering details on connection methodology can be found elsewhere [(7)] but the authors have since developed a system of welding which relies upon pre-wired and sheathed studs, and a specially developed stud welder, which uses a "gun" type head (see Fig. 2) that can deliver rapid and reliable connections at a very fast rate, allowing all the connections to be made in minutes rather than the hours that they originally took.

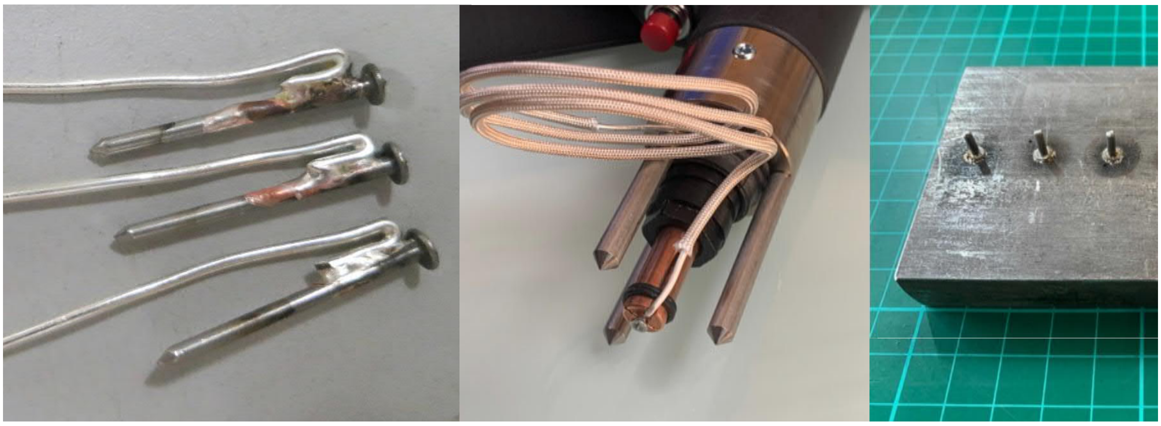

Figure 2. Left – pre-soldered stud connections ahead of installation, Mid – modified stud gun head, Right – rapidly welded stud array (minus wiring)

This process can now be enhanced even further by using 3D printed profiled "jigs" which act as locators to ensure the arrays of connections are appropriately positioned, and the wiring suitably oriented and strain-relieved – creating a single "umbilical" which is pre-manufactured at base, and can then be quickly installed in the industrial context. This is especially important for sites such as steam header pipe welds, where multiple locations along the weld have to be monitored simultaneously. Normally, 4-8 connection locations are sufficient to adequately monitor one side of a weld, so a total of 16 "sites" will cover the complete weld. This generates a substantial umbilical containing nearly 100 sheathed wires. Currently, the 3D printed jigs are polymeric, so limited to room temperature use. Their use for high temperature installations is still recommended specifically to speed up the connection process, but they are designed to be subsequently separated from the studs after welding and removed.

Silver wire of ca 1.5 mm diameter was used for the current supply lines, and 0.5 mm for the signal lines. Silver was found to being extremely easy to handle in the field, thread through insulation, and solder in place. Its low resistivity meant that it was an ideal choice to be able to share AC and DC wiring, thus simplifying the umbilical (at least until it was necessary to separate routes closer to the EPD instrumentation, whereupon conventional polymer sheathed, copper cabling is employed).

Silver resisted the high temperature conditions admirably, and even after 10,000 hours of exposure, was always bright and free from oxidation, unlike the stainless studs which became heavily oxidized (see Fig.3).

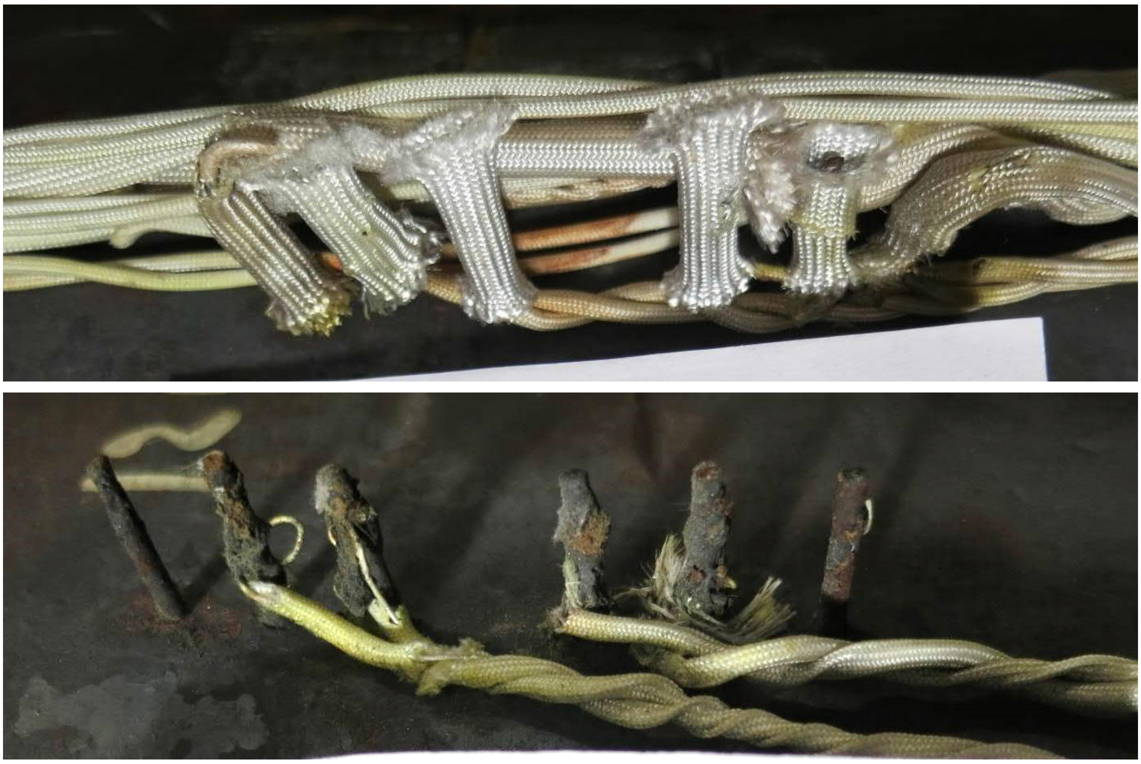

Figure 3. Top – as made stud/wire connections ahead of creep test, Bottom – after 10k hour test duration – note unoxidized silver wire

Typical lead lengths were 3 metres from connection point on the test vessel, to a nearby junction block (external to the test furnace), whereupon connection to a set of signal and current multiplexers (and thence to the AC and DC instruments) was via shielded twisted pair copper cable.

Wherever possible (and to help eliminate interference or “pick-up” in ACPD situations) all wire pairs (signal as well as current) were twisted together, although this was minimised to avoid damaging the high temperature insulation over the wires. As a consequence of each weld containing two adjacent HAZ locations, each HAZ was monitored separately. A total of 6 studs were positioned in-line across a weld to create a measurement “zone” with the outer two studs delivering the requisite EPD excitation current, with the two inner pairs straddling each HAZ, and acting as the EPD measurement points (see Fig 4). Several “zones” along any one weld were thus covered.

Figure 4. Left – Stud connections after installation on horizontal vessel, Right – close up of a set of 6 studs, the outer two for the excitation current and two inner pairs for the signal from each HAZ

Connection failures were common at the start of the work, but once the stud welding parameters had been optimized, these disappeared. Some work was attempted using nickel wire, but this was not as reliable, and proved more problematic to install, given that the higher electrical resistance of nickel required thicker wires to be employed (for the current supply leads).

The EPD instrumentation was placed external to the furnace and blast zone (necessary because the vessels were pressurised), and placed under the control of bespoke software which could be accessed across the Internet, permitting the easy transfer of data for regular interpretation. Figure 5 shows a schematic of what a real-world AC/DC EPD system would entail, and this was very much based on the pattern followed in the study described here.

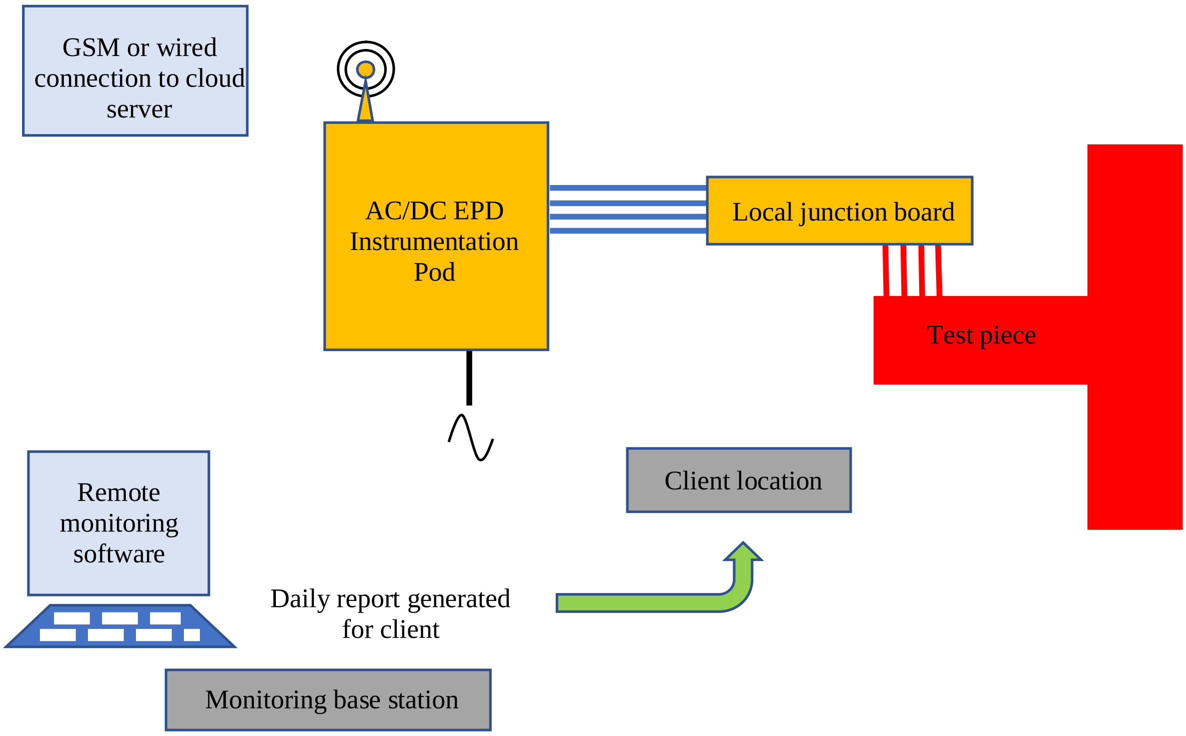

Figure 5. Schematic of a full AC/DC EPD system in a condition monitoring role. The local junction between RT (copper) and HT (silver) wiring is undertaken as soon as the HT wiring exits the hot zone

Skin depth calculations for P91 steel, at the chosen excitation current frequencies suggested that even at the lowest operating frequency of 300Hz, for the ACPD variant, the skin was significantly thinner than the specimen wall thickness (ca. 5mm compared to 25 mm). This meant that the ACPD readings were only expected to reveal defects and/or microstructural variations that were close to the outer surface of the vessels. Past experience, however, suggested that crack development would initially be internal before travelling to either the outside surface or the inside (back-face) of a vessel. The lowest excitation frequency (300Hz) was therefore expected to give the best chance of showing any internal or back-face defect. For reasons which are not entirely understood, subsequent work [(11)] has indicated that a "sweet-spot" in ACPD frequency of around 3 kHz exists where sensitivity to incipient damage is maximised, so the parameters used in the original study may not have been optimal. It should be noted however, that this higher frequency was found to be more effective when examining creep-tested specimens in a laboratory context (as opposed to on-line and continuously monitored). The specimens in the higher frequency study were also cut from larger welds, so differed significantly from a "real" pressure vessel where the skin effect would have substantially limited the penetration of the excitation current into the zones likely to first suffer creep damage.

The AC excitation current was set to 2 amps for all measurements. In contrast, direct currents of ca. 50A are sometimes required for comparable signal magnitudes, but this is often not possible using commercial equipment if the lead lengths are long (and hence the overall resistance of the current path is high). High currents can also cause specimen heating and this can (and did) lead to drift in DC signals if currents higher than about 15A were employed, so this was the default excitation current for the DC variant. A similar set-up was employed for other vessels in this study – one P92 vessel and a further P91 vessel, the only differences being that these latter vessels were mounted horizontally, and no external axial load applied.

3. Results and discussion

The study generated a mass of data over its 4 year period and much of this is described elsewhere [7], however the broad lessons for the use of EPD in a continuous monitoring role to detect incipient creep degradation, all the way to the final throes of a vessel's life, can be drawn. Figure 6 shows a plot of data extracted from a representative data file and illustrates a typical DCPD response over a total period of just over 2.5 months from an adjacent pair of HAZ locations (designated "x" and "y") on the tested P92 vessel. There is clearly a large variation in signal magnitudes over time (this was mirrored by changes in monitored ACPD too).

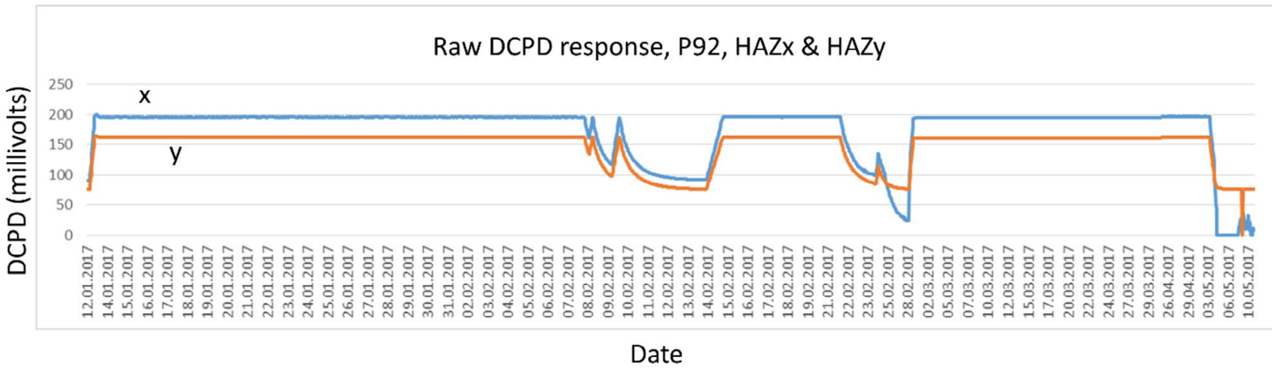

Figure 6. DCPD over time (4 months) – initial rise to level due to heat up of furnace, with subsequent transients being due to temperature control issues with furnace. The massive swings far exceed anything due to incipient damage by several order of magnitude.

The fluctuations seen amount to several 10's of % of full scale, which was eventually found to be substantially in excess of any fluctuation attributed to incipient damage (over months of exposure) – hence the early comment that changes due to cavitation and micro-crack development are likely to be very subtle. Once a crack had initiated and grown to be a substantial fraction of the specimen wall thickness, large changes in signal level might be expected, and indeed were observed, but clearly the fluctuations seen in Figure 6 recover in magnitude and level, and are definitely, therefore, not due to specimen cracking. Furthermore such changes were often observed early on in the projected lifetime of the vessel, so could not be reasonably ascribed to cracking, in any sense. Most of these fluctuations were subsequently traced to changes in specimen temperature and/or failure of the apparatus applying internal pressure to the vessels.

To help deconvolute and deal with such signal changes, it was necessary to “normalise’ the data. In laboratory based EPD, during elevated temperature testing, it is normal to employ a reference channel to normalise for temperature fluctuations. A ratio of active/reference EPD is then calculated and this should be immune from changes in temperature. Normalisation by division was indeed employed in the pressure vessel study described here, but in the final analysis, normalisation was often found to not totally eliminate experimental fluctuations, most probably because the effect of temperature on the signals is likely to be non-linear or may involve signal components that are additive, and so cannot be completely eliminated through a simplistic mathematical division of active versus reference signals. This is especially expected to be the case when changes in pressure (hence strain) are factored in. ACPD is strongly affected by strain (in ferritic materials) (2) and not in a linear fashion.

Notwithstanding the above, a form of normalisation was employed in a post-processing sense. Thus changes in signal magnitude in active areas were compared to those seen in passive/reference areas and if a similar trend was observed, the transient data could be offset or discounted totally – especially if the variations seen were small in duration (in relation to the overall testing duration). For this form of “normalisation” to be applied effectively, other signals (such as temperature, pressure and /or strain) clearly need to also be monitored, compared and interpreted alongside the EPD data, if any certainty is to arise in practice. Other filtering methods can be employed to remove solitary transients which are clearly “rogue” points and act to mask the longer term trends.

Figure 7 illustrates what can be done using the approaches discussed, in this case to the data from the P92 vessel. The data is now (perversely) far noisier than before, as autoscaling has been employed to essentially raise signal gain (only possible after the larger transients had been removed).

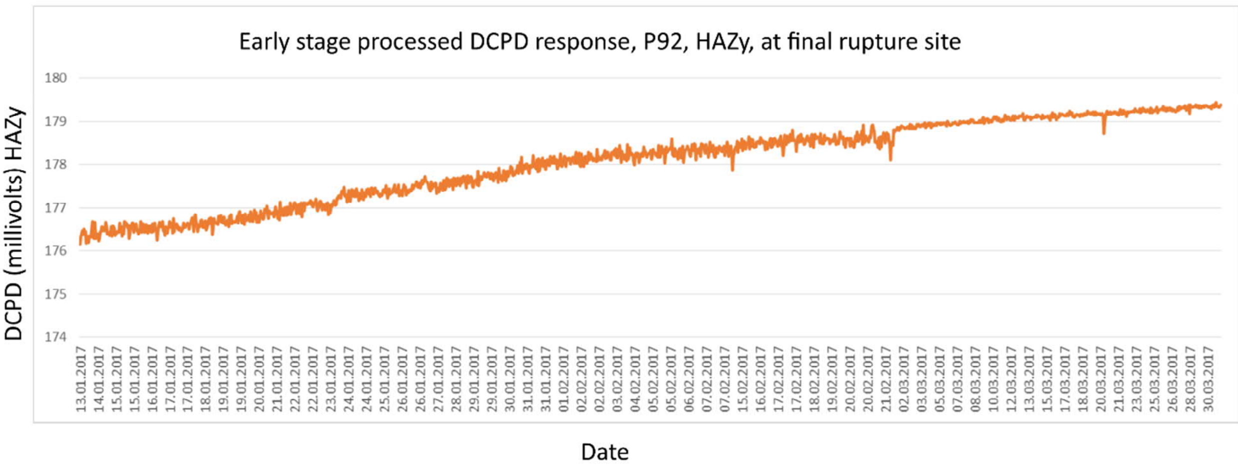

Figure 7. Processed DCPD over time (2 months) – transients have been removed, and data autoscaled to the point where signal noise can be detected. Slow but steady rise due to possible incipient damage then emerges.

The y axis scale now reveals that noise in the EPD is at a level of 10's of nanovolts – and hence is more likely to be a reflection of overall instrumental noise. Emerging from this noise can be seen a clear trend however – a gentle but steady rise in the EPD which is much more likely to be as a result of the development of creep damage. Given that this data set was obtained from a zone on the P92 vessel directly over where final rupture occurred, the authors had great confidence that they were detecting incipient damage.

Figure 8 reveals what was observed to happen to the EPD once a "real" crack had initiated in one of the circumferential welds, in this case in one of the P91 vessels. The presence of the crack was confirmed after catastrophic failure of the vessel had occurred.

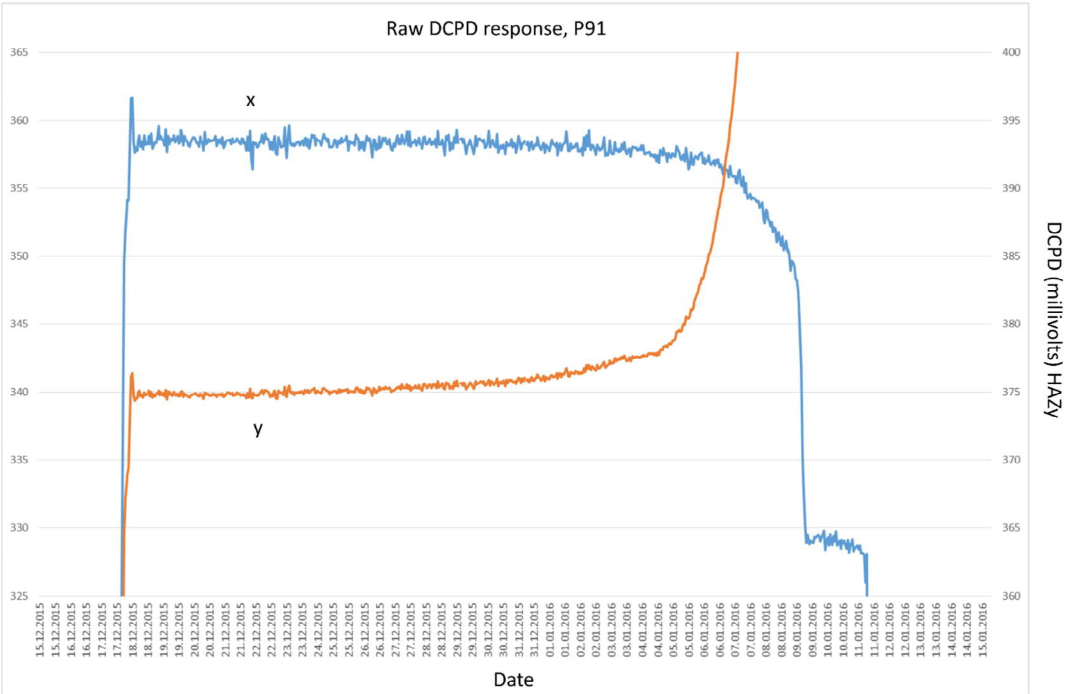

Figure 8. Raw DCPD over time (2 months) as final failure occurs – steady rise overtaken by exponential rise as crack propagates. Shielding effect on adjacent HAZ means complimentary DCPD drops.

It should be noted that, as before, two signals were being monitored at this zone, namely one from either side of the weld, so that both HAZ were covered by AC and DC EPD measurements. The DC trends appear to work in opposition to each other with the one HAZ zone showing a clear exponential rise associated with a rapidly propagating defect, but the complimentary HAZ trace shows a gentle decline. The explanation for this is easily understood if it is noted that both monitored zones are being fed the same excitation current and lie in line with each other (in terms of current flow) hence the growing defect will a) raise the DCPD (as conventionally expected) but b) divert the current flow away from the adjacent monitored HAZ such that it appears to show a reduction in measured DCPD. In other words a developing defect shields the response from an adjacent monitored zone, so as one signal rises, the other falls.

It was clear that the change in the DCPD was very dramatic and highly definitive, when in the latter stages of failure (the last two days), but that nevertheless, a far subtler rise was seen at least two weeks ahead of failure. Such a gentle change would normally be deemed insufficient to draw many conclusions from - however, when considered together with the drop seen in the adjacent HAZ's response, a greater degree of certainty can be assumed that creep damage was developing – especially whenever a similar "pattern" was observed in other monitored areas. Additionally, when the complimentary ACPD response is considered alongside, a stronger pattern begins to develop - Figure 9 illustrates the corresponding ACPD traces, for the same locations on the P91 vessel, and here it can be seen that as the DC traces rise, the AC responses drop. Unlike for DCPD, this occurs on *both* HAZ positions and the drop continues until such time as the DC trace has begun its exponential rise, at which point the AC response also turns and appears to follow suit by rising almost vertically (signifying rapid crack propagation).

Figure 9. Raw ACPD over time (2 months) at final failure – steady drop overtaken by exponential rise as crack propagates. Shielding effect on adjacent HAZ means complimentary ACPD drops. Transients not removed.

The explanation for the AC behaviour is not obvious and relies upon the knowledge that in ferritic materials, ACPD signals are sensitive to stress (strain in reality) [2, 12] as highlighted earlier. This is a result of the change in magnetic permeability that occurs when the grains containing magnetic domains are strained. As a result, in a ferritic material under a uniaxial stress, the ACPD measured axially has been observed to drop as the stress rises. In the monitored pressure vessel, the developing defect will be expected to raise the local stress to a point where the ACPD may indeed be affected by the stress concentration. Of course, the ACPD could also be responding to a rise in the general strain as a consequence of creep seen globally across the specimen. Strain gauges fitted to the pressure vessels did indeed register a gradual, if small rise, in global strains with time.

Overall then, given that the “true” ACPD is normally only sensitive to surface breaking defects (as it relies upon the skin effect to generate a rise in path length as a defect grows) it is likely that the AC response over time will first drop (due to strain effects) before finally rising (presumably once the defect has become surface breaking).

When taken together, the drop in AC with the rise in DC, and the drop in DC on one HAZ, with a rise in the other, constitute a characteristic “signature” which could greatly lengthen the warning period ahead of an impending failure when compared to the case of monitoring a single EPD response using one or other of the EPD variants.

That said, it should be noted that the signature described here (and elsewhere [(7)]) is particularly confined to a double HAZ situation in a weld in a ferritic material, and may well be different in other materials and testing geometries - however it is not unreasonable to suggest that alternative signatures could be identified, in other testing contexts.

The pattern of AC and DC EPD responses was repeated in all of the pressure vessel test conducted to failure. On one notable occasion, a decision was taken to prematurely stop a P91 test ahead of a scheduled outage, given the observed changes in the EPD responses. No surface breaking defect was observed (and none was found subsequently in the internal surfaces of the vessel), but ultrasound inspection (UT) was implemented and confirmed the existence of a small degree of sub-surface cracking. Subsequent sectioning and metallographic examination supported the UT and EPD results, and revealed that as well as an internal crack, substantial cavitation damage had occurred in the vicinity of the developing defect. The defect was also significantly larger than the initial UT had suggested. Conservative estimates of the length of warning that the EPD monitoring system would have given test operators of a leakage in this vessel, via a surface breaking defect, were in the region of two to three weeks. This may well be sufficient notice for many plant operators.

The subtle (relatively), but steady, rise in DCPD seen in Figure 7 was actually present for some 2.5 months (ca. 1600 hours) before the test was terminated and the P92 test vessel examined using UT. No crack-like defects were detected, the EPD connections re-made, and the vessel was put back under test. The gentle rise in DCPD was observed to continue (at a similar, almost linear, gradient) until final cracking and failure occurred some 2 months later, whereupon a rapid rise in DCPD was observed (similar to that seen in the earlier P91 tests). The percentage change in DCPD amounted to less than a 1.5% rise over the initial 4.5 months, whereas the change in the last few hours of life amounted to over 100%. In this particular test, it was highly unlikely that a crack-like defect existed 4.5 months prior to failure, so lending weight to the notion that the subtle change in DCPD may well have been due to incipient damage.

The longevity, expense, and complexity of the vessel tests limited the ability to reproduce these observations, but of the three tests conducted to failure (2x P91 and 1x P92), all three exhibited modest initial rises in DCPD readings close to the ultimate failure location.

Typically, over the total testing period of ca 10k hrs, the steady rise in DCPD, which we tentatively attribute to the build up of cavitation and micro-cracking saw less than 5% rise in DCPD over the starting EPD values, but this was sufficient to signpost the build-up of creep related damage.

Unfortunately, the testing timetable precluded termination of any test in the early stages of damage development and this particular study was more concerned with end-of life determination, rather than remaining life prediction. These tests were therefore open to criticism that the changes in EPD seen could not be categorically ascribed to incipient creep damage – and in particular to the formation of creep cavitation. This prompted a follow-on study where controlled laboratory testing, (on specimens taken from interrupted creep tests) were used to help determine the underlying phenomena responsible for the changes in AC and DCPD. This was done as part of wider research with several academic and industrial partners to better understand creep in P91 (particularly weldments) with the ultimate aim of being improved on-line and off-line NDE methods for remaining lifetime prediction. The results of this follow-on study are fully reported elsewhere [11] but it is helpful to discuss some of the work here, especially given the relationship of this more fundamental study to long term monitoring, both past and future.

For this interrupted creep study, small test specimens (130 x 10 x 4.5mm) were prepared (and creep tested) by research partners and consisted of P91 material cut from a large (160 mm plate) pressure vessel multi-pass weldment, (Fig. 10) so as to contain 50% base metal and 50% weld metal, with the associated main heat affected zone (HAZ) located approximately mid-span along the specimen's long axis and loading direction. Once again, failure was expected to initiate in the HAZ of the welds by Type IV cracking. It was these vulnerable zones that were monitored by the EPD system in the original online EPD study. Multiple specimens were machined and creep tested, under uniaxial load, at two temperatures (600 and 620 ^{0}C) for durations that corresponded to various (predicted) life fractions. In addition to EPD, a range of other characterisation techniques were deployed such as electromagnetic (EM) tests (e.g. magnetic Barkhausen noise (MBN) and measurements of magnetic permeability), metallography, Transmission Electron Microscopy, and Atomic Force Microscopy. For EPD, electrical connection to the specimen was made via sprung loaded pins but rather than being handheld, these were mounted in a computer-controlled X-Y table, so that surface scans of the specimens could be achieved. Computer software controlled the scanning procedure and, in this way, both area scans and line-scans could be made across the surface of a specimen, either employing DCPD or ACPD. Results were processed in several ways – firstly to ascertain whether absolute changes in EPD were detectable, but also to judge the changes in EPD when scanning along a line down the tensile axis of the specimen.

Some of these "line-scans" are shown in Fig 10 and 11, given their relevance to the online data already discussed.

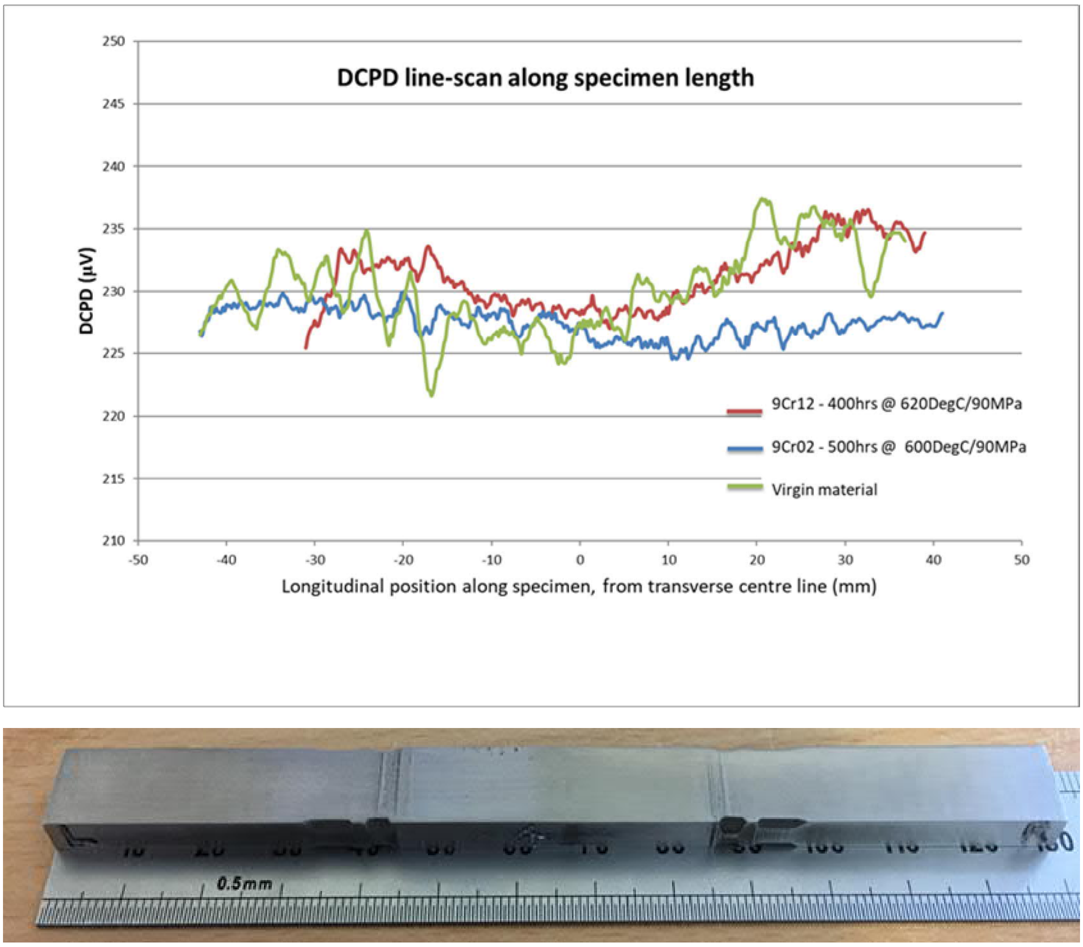

Figure 10. Top - DCPD line-scans along interrupted test specimens (bottom). Life fraction was estimated to be less than 20% for these specimens over virgin material (also shown). No convincing trends can be detected.

The results for DCPD scans were disappointing, and showed no statistically significant trend of absolute (averaged) DCPD with life fraction, although noticeable differences in DCPD level when traversing a HAZ were observed, indicating that DCPD is sensitive to microstructural effects. The reasons for this, and the contrast with the online studies, are manifold but could simply be that the test specimens were not subjected to true life fractions. Creep lifetimes are notorious for displaying large scatter and some of the pressure vessels in the original on-line study had been predicted to fail at 50% of their final (observed) lifetime. When these lifetimes are modelled to be in the tens of thousands of hours, a 100% error came as something of a shock. What is also true is that the DCPD results were very much influenced by the location of the measurement on the specimen – with substantial edge effects seen in the area scans (unsurprising given the small size of the specimens). More details are given in the authors' earlier publication [(11)] but these outcomes for DCPD further reinforce the notion, cited earlier, that the subtle changes in EPD are best detected via continuous monitoring, irrespective of the care and attention taken with interrupted "spot" measurements.

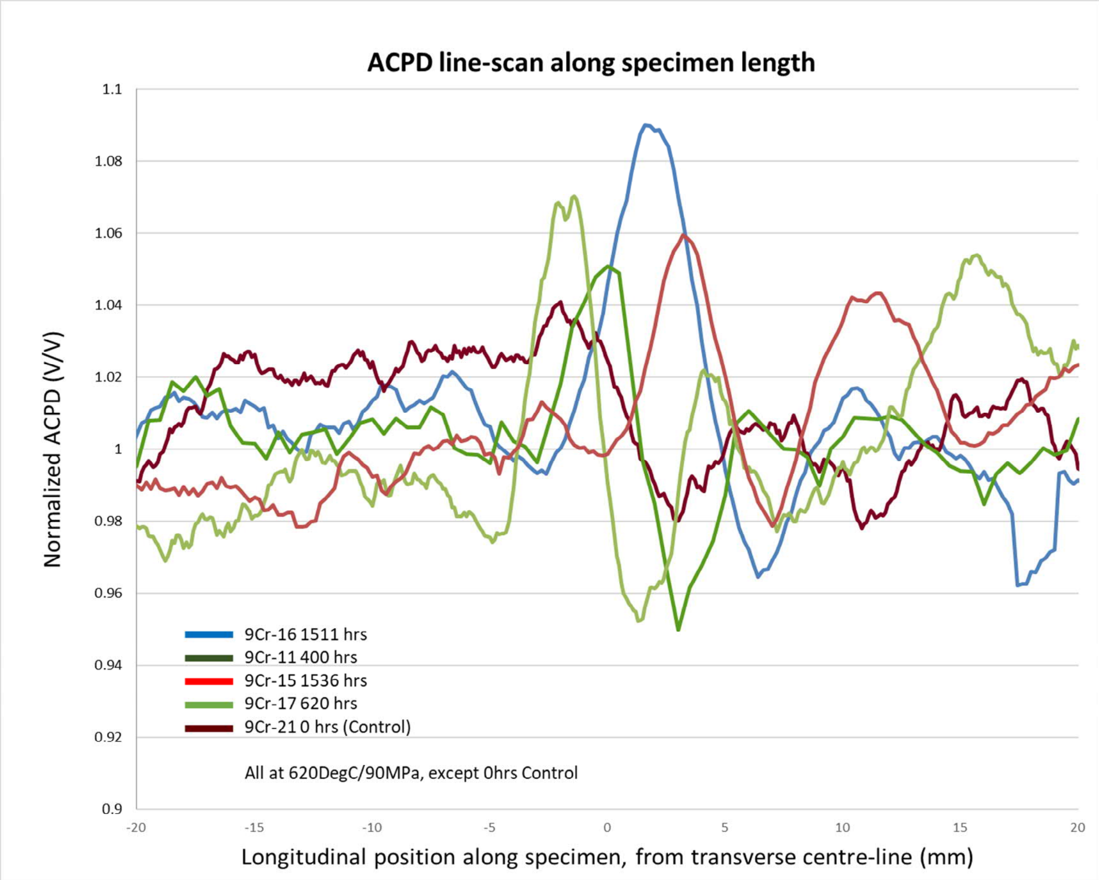

Figure 11. Top - ACPD line-scans along interrupted test specimens. Definite peaks are detectable, with central peak corresponding to location of HAZ. Further peaks (multiple passes?) can also be detected.

For this latter study, ACPD results showed a much more positive correlation with the previous on-line work, as well as far more dramatic changes in the signal level when traversing a specimen. Peaks in the absolute ACPD were detected at the HAZ (as opposed to the level changes seen in the DCPD results), and when the peak heights were plotted, a definite trend with life fraction was detected (see Fig. 12).

This trend was tentatively ascribed to a rise in the cavitation damage within the HAZ of the specimen (which appeared to correspond well with the location of the peaks in the line-scans). That said, what is significant about the ACPD results to the present discussion was the trend seen with the absolute (line averaged) ACPD taken across the whole specimen. This is shown in Fig. 13, and revealed a definite drop over time, before recovering a little.

The response seen in Fig 13 ties in beautifully with that seen in the on-line testing – namely a steady reduction in ACPD over time, until cracking becomes dominant and the PD begins to rise (or at least recover).

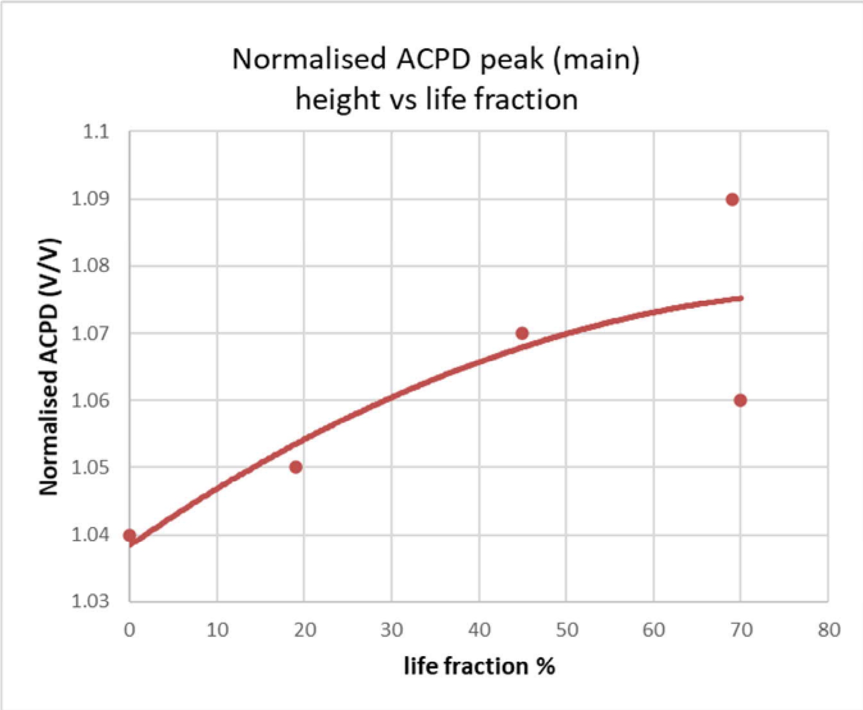

Figure 12. Variation in ACPD peak height (main peak) with life fraction (estimated)

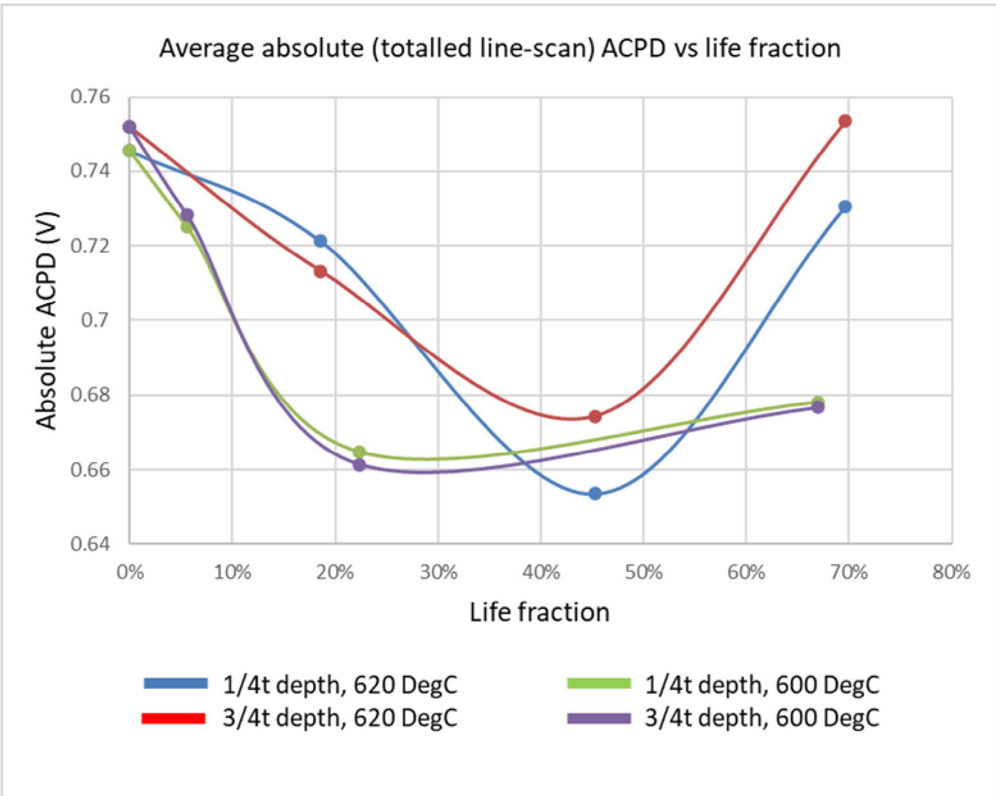

Figure 13. Variation in average ACPD (across main part of specimen) with life fraction (estimated).

Measurements of magnetic permeability conducted by partner researchers (and reported elsewhere [(13)]) showed a similar trend in response – with the permeability dropping almost immediately with life fraction, and then reaching a minimum at about 50% of life. This again was encouraging in so far as the changes in ACPD are expected to be sensitive to changes in electromagnetic properties such as permeability, given they influence parameters such as the skin depth.

In summary, what was originally presented as a challenge to the application of EPD to on-line condition monitoring – namely the interpretation of the EPD responses obtained, doesn't now seem quite so challenging. The complexity of the signal obtained, remains, but by careful "processing" the various changes seen can be ascribed to different mechanisms, leading to the removal of some signal variations, and the enhancement of others. The deployment of the combination of AC and DC EPD allows further analysis and discrimination against the effects in operation – such that changes ascribable to incipient creep can begin to be detected in the data sets. More work needs to be undertaken, particularly towards the further understanding and testing of "signatures" in EPD responses. At present, it is recognized that the current signature may only really apply to a select few testing scenarios, so more work needs to be done in this respect. Ultimately, there is a need to pool all this knowledge within monitoring software to provide an automated response during continuous monitoring activities. The technology is nevertheless now mature enough to be formally employed in the field. Once the existing signature has been re-confirmed (and done so within fully industrial contexts) and other signatures recognized, the pooling can be enhanced. The use of AI methods and machine learning may well permit new signatures to be recognized, during formal condition monitoring, and deviations from older ones confidently ascribed to explicable phenomena and plant events.

5. Conclusions and wider implications

The EPD work carried out to date by the authors suggests that EPD, and in particular the combination of AC and DC EPD is sensitive to both the incipient damage stages of creep in metallic components, as typified by cavitation and micro-cracking, as well as the final stages of macro-crack development and propagation. Chief in generating this positive outcome has been the realisation that the strength of EPD in detecting early-stage damage, relies upon its use in a continuous monitoring guise, as opposed to the more often applied "spot-checking" mode inherent in the NDT manifestation of EPD. The changes in signal magnitude commensurate with incipient damage are simply too subtle to be within the bounds of the errors that can occur in spot-check measurements. When used in a continuous monitoring form, however, and when allied with high sensitivity and, crucially, high stability EPD instrumentation, these subtle (and often very long term) changes are revealed for what they really represent. In the authors' work, once larger transients were stripped out, locations where failure subsequently developed did show subtle, but definite, changes in EPD months prior to rupture. In particular, DCPD responses were seen to rise in a linear fashion for up to 4.5 months before final fracture.

Additionally, the combination of ACPD with DCPD, and the tendency of these two variants to respond differently to a variety of stimuli in addition to crack growth, as well as their different responses to crack growth per se, has further assisted in the task of permitting the detection of early-stage creep damage.

The emergence of the belief that a combination of ACPD and DCPD can help in interpreting creep behaviour, and that a 'signature" response is present, is a definite step forward. In the tests conducted, a developing defect, such as a crack, was expected to increase specimen resistance (hence raising the EPD in the case of DCPD), but could also raise local section stresses hence lowering ACPD. Development of global strains across the test specimen would be expected to have a similar effect on the ACPD. This would continue up to a point, and then the signals would rise, as the contribution from an emerging defect begins to dominate. A further characteristic of the signature response (but one dependent upon the use of pairs of signal pick up points - one for each HAZ of a monitored weld) was where the signal straddling the developing defect increased, whilst the one on the complimentary HAZ reduced. This can be explained by the developing defect's additional ability to redirect the flow of excitation current away from the second HAZ measurement point. For sure, other signatures will exist, but for now, the reported trends were demonstrated to provide irrefutable notice of impending vessel failure.

There therefore appears to exist a definite synergistic benefit in using the combination of the two EPD variants, and one that far outweighs the additional expense and complexity of employing two sets of instrumentation.

Shared cabling, and a single set of contacts for both AC and DC EPD has greatly helped simplify physical installations and the clear challenge facing EPD instrumentation manufacturers is to generate a single instrument that combines both variants in a one "package". This challenge is not without its difficulties, as the fundamental operation of the electronics is very different between variants (in particular the noise reduction principles employed and the stability circuitry for the excitation current supplies).

The challenge of finding the engineering path to generating reliable and long-lived sets of electrical connections to the test piece has largely been met however, with practical installation times now being a matter of hours rather than days, and connection lifetimes measured in years rather than months. This has mainly been achieved via attention to the materials employed and the welding equipment and methodology in place. Further gains in this area are likely with the generation of tailored umbilicals and jigs manufactured off-site from 3D scans or existing engineering drawings, to ensure fast installation and minimal on-site set up. Once this is achieved, the engineering necessary to monitor the EPD responses remotely is largely in place, but there may well be further gains to be had from the application of AI to the processing of the signals received back at the monitoring location, particularly given the rather manual nature of the monitoring that has been achieved to date.

Thankfully the notion of a signature identifiable in the DC and AC EPD signal responses, that signifies the development of creep damage, if maintained and reinforced in follow-on studies is likely to make unattended data interpretation even more reliable.

Any installed EPD system is envisioned as a back-up to the established round of outage and inspection that is common in the industry, and not as a replacement. It is ideally suited to the monitoring of component parts that are close to the end of their design lifetime, or have been subjected to an offline inspection in order to extend their certified lifetime beyond the original design life – and hence are at particular statistical risk of failure. Continuous online monitoring of such components, usually covering highly stressed areas or areas likely to be susceptible to failure, offer the plant operator a belt and braces approach to their risk assessment – and whilst an absolute guarantee of efficacy can never be given, the likelihood of a catastrophic failure must be reduced by the adoption of such an approach.

The success which the combination of AC and DC EPD has allowed in terms of detecting creep related phenomenon that are often subtle precursors to more substantial crack development suggest that further benefits are likely to accrue from a similar application to other time-dependent degradation mechanisms in metallic materials, components and structures. In particular, the expectation that EPD (or at least the combination of DC and AC EPD) could be employed to detect the onset and development of hydrogen embrittlement (HE) and high temperature hydrogen attack (HTHA), both of which could progress through a micro-cracking stage, before the latter subsequently join to form larger defects, ahead of final fracture. As far as the authors are aware, no such EPD studies have been conducted, not even to the extent of evaluating the sensitivity of either EPD variant to HE or HTHA. It is the view of the authors that such studies would now be worth undertaking, as any methodology or technique that can provide an early warning against either of these two serious degradation phenomena in metals, is worthwhile having as another weapon in the condition monitoring armoury.

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