Introduction

DC electrical resistance (ER) measurement techniques are an established way of detecting, or monitoring changes in, metal surfaces due to corrosion, erosion, crack or pit propagation. In the 1990s, Rowan Technologies Limited (RTL) developed instrumentation that uses ER techniques for on-line monitoring of high temperature corrosion in steam generation boilers and other high temperature plant [1]. The range and application of RTL’s ER monitoring systems has since broadened considerably.

The primary role of RTL’s systems is to monitor the degradation of, or growth of defects in, metal surfaces as time progresses [2, 3]. However, there are particular circumstances where systems can be used for ‘one-time’ measurements that can directly detect the presence of isolated pits or cracks on internal surfaces of pipes or other items of plant.

This article provides an overview of these different techniques, considers factors that can influence measurements, and describes the application of RTL’s portable scanner system to these techniques.

Measurement Fundamentals

During ER measurements, a DC current is applied to the surface between two electrodes: one for current into the surface (current source), and one out (current sink). Whilst current is applied, two separate electrodes measure the resulting voltage drop in the region between the current electrodes, Figure 1. Ohm’s law is then used to derive a measure of resistance \( \text{ER} = \text{voltage/current} \).

Other factors aside, all growing surface defects have the effect of increasing the measured ER values, Figure 2. The effect is more pronounced for some surface changes than for others: uniform corrosion
or erosion produces an increase in overall current density, hence an increase in measured resistance. For cracks and pits, the change in current density is localised around these defects and, when these are shallow, the effect on measurements are considerably smaller.

**The Flow of Electrons**

Electrical current is the flow of electrons along a voltage gradient. When current flows through a wire, electron flow is tightly constrained within it (one-dimensional flow). However, for larger plant components e.g. pipes and tube walls, the electrons have much greater freedom of movement (i.e. multi-dimensional flow).

Free electrons have a natural tendency to repel each other. On entering a metallic surface through an electrode (i.e. current source), they immediately try to spread out and away from each other on their journey to the current sink. This effect is particularly marked on an unbounded surface when current source and sink are two point electrodes. The pattern of current flow is similar to that of iron filings around a bar magnet, Figure 3.

In the case of a pipe, with a point current source and sink positioned along the pipe axis, the current again rapidly spreads out. Assuming an adequate distance between source and sink, the current will quickly and uniformly distribute itself around the pipe circumference.

So, current will try to spread out rapidly between a point source and sink along any metal surface, as far as the surface boundaries will allow. This can have advantages for certain ER measurement applications, in helping to create uniformity of current. However, current density drops as the current spreads, resulting in weaker voltage signals. Being aware of the current behaviour helps the user to optimise the ER measurement systems for maximum effect.

**Periodic Monitoring of Surface Changes**

**The Effects of Surface Changes**

RTL’s portable systems are principally designed to monitor surface changes by performing periodic measurements, typically at intervals of weeks or months. The type of surface change has a big influence on detectable increases in measured resistance:

**Uniform Corrosion and Erosion:** In several respects, this is the simplest surface change to monitor: if the metal wall halves in thickness, due to uniform corrosion or erosion, the measured resistance will double. Halve the thickness again and the resistance will double again, and so on. So the increase accelerates as the wall gets thinner. Also, for a uniform surface thickness, it doesn’t matter where the current and voltage electrodes are placed – the results will always be the same.
Modelling of different surface geometries enables increases to be translated into metal loss and corrosion rate. Where the start thickness is known, the remaining wall thickness can be determined.

**Cracks:** A single shallow crack only has a small localised effect on current flowing perpendicular to it, Figure 5a. Multiple surface cracks have a greater influence on measurements and, if the crack density is high enough, the effect can be similar to that of uniform corrosion, Figure 5b.

For shallow cracks, increases in measured resistance are initially small. As the crack deepens, increases in resistance accelerate exponentially and so become easier to measure. Figure 6 shows a steel block with a single cut in the lower surface: as the cut is made deeper, the measured resistance increases more rapidly, as shown in the graph.

Positioning of electrodes also affects measurement sensitivity: the closer the voltage electrodes are to the growing crack, the greater the observed increases. RTL uses finite element (FE) modelling to translate these increases to crack growth.

**Surface Pitting:** The effect of small pits on current flow is highly localised, akin to water negotiating its way around rocks on the surface of a river bed. This means that the influence of a single shallow pit on ER measurements can be tiny, unless the electrodes are positioned very closely to it. A high pit density, or larger single pit, will have a greater influence on readings.
Surface Temperature

As a general rule, the ER of metals increases with temperature and this affect varies from metal to metal. When taking measurements over a period of time, variations in metal temperature need to be considered, and if necessary compensated for. There are two approaches to achieving this:

The first method is to monitor metal temperature whilst at the same time monitoring resistance. Then compensate the resistance readings for any temperature variations, so that any underlying increases in resistance, due to changes in the metal surface, can be established.

The second method makes use of a ratio technique: two resistance measurements are made, the first is of an area subject to surface changes (e.g. crack growth) whilst an adjacent (reference) area experiences no surface changes. Taking the ratio of the two measurements means that the effect of any temperature change over time, experienced by both areas, will cancel out: changes in the ratio then simply reflect the surface changes of the first area. Figure 6 illustrates the principle for a single crack at a pipe weld: the measurement area is across the weld whilst the reference area is adjacent to it.

Which approach is used will depend on circumstance: sometimes a practical reference area is not available and so temperature measurement and compensation is needed.

Electrical Interference

ER monitoring systems often measure voltage signals down to the sub-microvolts level and so are sensitive to interference. To counteract this, RTL’s systems employ signal filtering and averaging where needed, and signal cabling is shielded where required. Larger currents help to mitigate this effect by producing higher measured voltages, so improving the signal to noise ratio; practicality and cost tend to dictate the maximum current used for a particular application.

‘One-Time’ Measurement for Defect Detection

So far, we have discussed the use of systems to monitor changes in surface conditions by examining trends in ER measurements over time. However, under certain conditions, it is feasible to use ER measurements to directly detect the presence of defects as electrodes are moved along a surface. By way of example, if the voltage electrodes are positioned either side of the defect then, for a 50% surface penetration, a single pit can produce roughly a 10% increase in measured resistance and a crack a 25% increase in resistance.

The general principle is as follows: apply a current to the surface under investigation; this can either be continuous or periodic. The ideal current is one of uniform current density – variations in current density will cause unwanted variations in voltage gradients across the surface. Now move the voltage electrodes across the surface, monitoring changes in voltage that might indicate the presence of a defect. The spacing between the voltage electrodes should be fixed at all times -
variations in spacing will have a direct effect on measured voltage. Knife-edge electrodes are normally used in practice.

**Current Density:** Creating a uniform current density along a surface is more straight-forward for some applications than for others. Earlier we discussed how surface boundaries ‘force’ the current to flow in a particular direction: in the case of a pipe, assuming sufficient distance between current source and sink, current will uniformly distribute itself around the pipe circumference. With no surface boundaries current can, and will, flow in multiple directions on its journey between source and sink.

RTL sometimes uses a technique for creating ‘uniform’ current flow on an unbounded surface using multiple current sources and sinks. This creates what we term a ‘curtain’ of relatively uniform current flow over a wide surface area, Figure 8.

The examples in Figure 9 show how the detection technique can be used in practice for detecting pits and cracks:

Signal ‘amplification’ can be achieved by locating current electrodes closer to the suspected defect. This produces a higher current density in the vicinity of the defect, so amplifying the voltage signals. In practice a two-stage process is needed: firstly, fix the current electrodes at a distance and then move the voltage electrodes over the surface. Then, where a defect is suspected, position the current electrodes either side of the area to be re-scanned. Knowing the relative positions of voltage and current electrodes, FE modelling can be used interpret the increase in resistance.

The requirements of uniformity (or consistency) of current, and of electrode spacing, have already been discussed. Several other factors also need consideration when applying this technique:
**Uniformity of Thickness**: Manufacturing tolerances in wall thickness might introduce a small degree of variability in voltage measurements as the voltage electrodes are moved over a surface.

**Temperature**: Uniformity of temperature will help optimise measurement quality. Off-line measurements may be preferable on site to help achieve this.

**Signal Magnitude**: Small signal voltages are susceptible to interference. The closer the voltage electrodes are together, or the thicker the surface, the smaller the signals will be. As high a current as is practical (to amplify voltage signals), combined with signal averaging, will help to minimise the effect of signal interference.

**RTL’s Portable Scanner**

RTL’s portable ER scanner system, Figure 10, has been developed for monitoring at a number of different locations within a large production or process plant. Its primary role is to monitor gradual surface changes over time, but may also be used for ‘one-time’ defect detection.

The system applies a DC current of around 10 amps to the surface under investigation and has a detection resolution of less than 0.2 microvolts.

**Monitoring of Surface Changes**

Here the system operator periodically returns to the same site location and compares data between visits to determine if any changes have taken place, for example, when looking for signs of crack growth at a pipe joint. Return visits might typically be every 6, 12 or 24 months. If changes in signal are detected, FE modelling can be used to help quantify defect growth.

The portable systems have in-built electronic multiplexing for up to 16 sensor locations. The channels may be configured in a number of ways: measurement of single areas, ratio measurements or scanning using a small sensor array. For periodic monitoring, factors that might influence the measurements need to be considered:

**Electrode Spacing**: Consistency in electrode position between measurements is critical: this is one reason why RTL normally uses fixed, welded sensors for its continuous monitoring systems. If welded sensors are not an option then electrodes can be pressed against the surface using straps or a mechanical jig, so ensuring good electrical contact with the ‘exposed’ metal. Consistency of position can be aided using washers adhered to the metal surface.

**Temperature**: Accurate measurement of surface temperature requires the use of thermally-bonded sensors and RTL’s welded thermal sensors are ideal for this purpose. The alternative is to use the resistance ratio method, a viable technique for crack monitoring at a pipe joint, for example.
**Metal Thickness:** Thicker metal surfaces result in a smaller voltage drop for any given applied current. Small voltages are more susceptible to sources of electrical interference; signal averaging then becomes more important to help ensure reliable and repeatable readings. The portable scanners are battery-powered, so avoiding possible AC interference from their own power source.

‘One-Time’ Defect Detection

The same portable electronics that is used for the monitoring of surface changes with time can also be used for one-time defect detection. Typically, when using the portable system for this application, current would be pulsed whilst the voltage electrodes are moved over the surface.

Assuming a surface that is relatively uniform in temperature, then temperature compensation is not required: this technique is purely designed to detect spatial, instantaneous changes in measured voltage across the surface as the voltage electrodes change position.

Future Developments

DC ER techniques are widely used for geophysical surveys to detect anomalies in the ground or for assessing different rocks or soils due to their differing levels of moisture. These surveys involve progressively bringing the positions of the current electrodes closer together so that the current does not flow as deeply into the ground.

The same technique could be used for pits, and especially cracks, located on the opposite metal face to the electrodes. For example, if the current electrodes are moved close together over a suspected crack, the current will not be able to fully penetrate the surface and the crack might not be detected. If the electrodes are progressively moved further apart then the current will penetrate deeper into the metal and the crack would then be detected and perhaps quantified, Figure 12. RTL are currently researching how this ‘ER tomography’ can be used in practice. The electrode design and application will be critical for this technique to be successful.

In Summary

When applying ER measurement techniques, different circumstances require different approaches to the technique employed, and factors that might influence measurements need to be considered. High measurement precision may be required, especially in the case of isolated, shallow defects.

Understanding the behaviour of current flow, the effect of surface temperature changes, and being aware of possible sources of interference, all help the user to optimise the measurement process, be it monitoring of gradual surface changes or the one-time detection of surface defects.
RTL portable ER systems provide a low-cost, convenient approach to applying a range of ER techniques that are both simple and effective. System portability and flexibility are the hallmarks of these systems, with the ability to detect cracks and other defects in a wide range of industrial plant components.

References