The Monitoring and Measurement of Surface Corrosion, Erosion and Defects using DC Electrical Resistance Techniques

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Introduction

DC electrical resistance (ER) measurement techniques are an established way of detecting, or monitoring changes in, the surface of metal components due to corrosion, erosion, cracks or pits. In the late 1990s, Rowan Technologies Limited (RTL) developed instrumentation that uses ER techniques for on-line monitoring of high temperature corrosion in steam generation boilers, alongside the monitoring of boiler wall thermal behaviour. The range and application of RTL's ER monitoring systems has since broadened considerably.

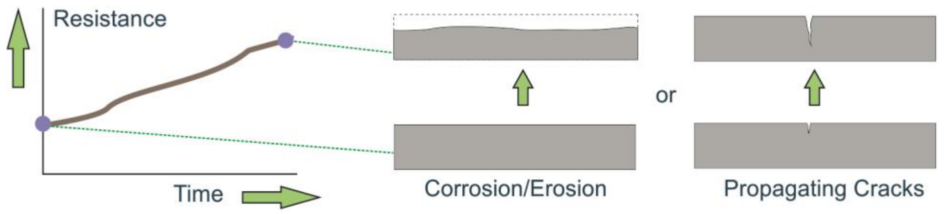
The primary role of RTL's systems is to monitor the physical deterioration of metal surfaces as time progresses, and this approach will be the main focus of this article. However, there may be particular circumstances where systems might be used for 'one-time' measurements that directly detect the presence of, for example, surface cracks.

This article provides an overview of these different techniques, considers factors that can influence measurements, and demonstrates how our systems are applied.

Measurement Fundamentals

During DC ER measurements of metal surfaces, a DC current is usually applied to the surface between two electrodes: one for current into the surface (current source) and one out (current sink). Whilst current is being applied, two separate electrodes measure the resulting voltage drop in the region between the current electrodes. Ohms law is then used to derive a measure of resistance (ER = voltage/current).

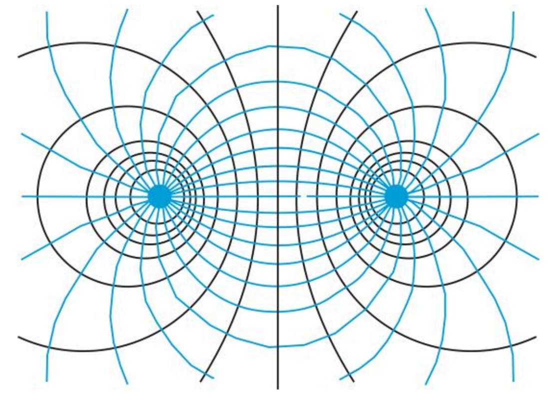
Other factors aside, all growing surface defects have the effect of increasing the measured ER values. The effect is more pronounced for some surface changes than for others: uniform corrosion or erosion produce an increase in overall current density, hence an increase in measured resistance. For cracks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



Surface Changes increase Measured ER Values: Increases will Vary, Depending on Application

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. However, for larger plant components e.g. pipes and tube walls, the electrons have much greater freedom of movement:



Current Flow on an Unbounded Surface: Lines of Equipotential are Black, Perpendicular Blue Lines Represent Current 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, as shown in the diagram. Interestingly, some electrons follow circular paths between source and sink.

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. Current density drops as the current spreads, however, resulting in weaker voltage signals. Being aware of the current behaviour helps the user to optimise the ER measurement systems for maximum effect.

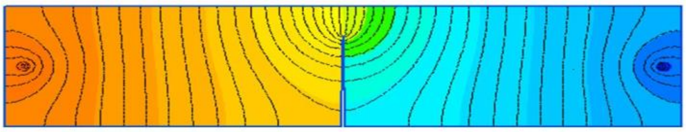
The Effects of Surface Changes

The type of surface change can have a big influence on detectable increases in measured resistance, as described below:

Uniform Corrosion and Erosion: In some 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, and so increases in measured resistance are initially very small. As the crack deepens, increases in resistance accelerate and become easier to measure. Positioning of electrodes also affects



Lines of Equipotential around a Single Crack. Current Density is Highest where Lines are Closely- Spaced

measurement sensitivity: the closer the voltage electrodes are to the growing crack, the greater the observed increases. RTL uses finite element modelling to translate these increases to crack growth.

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.

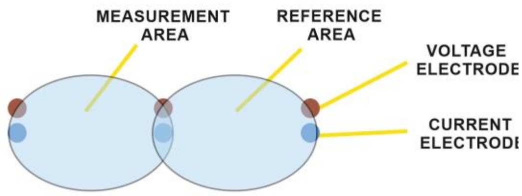
Surface Pitting: The effect of small pits on current flow is highly localised, akin to water negotiating its way around rocks on the surface of a river bed. This means that the influence of a single shallow pit on ER measurements can be tiny, unless the electrodes are positioned very closely to it. A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

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 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.



Example Resistance Ratio Arrangement

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 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.

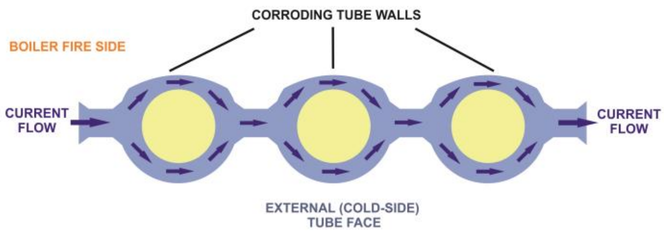
RTL's Industrial Applications – Continuous Monitoring

Fixed Scanner Systems and HFC Monitors

RTL's fixed scanner systems, for continuous monitoring, use electrodes and sensors that are welded to external surfaces. Welding provides several benefits: the welded 'feet' of RTL's thermal sensors provide a perfect path for heat transfer, allowing true surface temperature measurement. Welded sensor connections are robust, ensure solid electrical connections and, of course, never change position.

Scanner Sensor Array: Boiler Membrane Wall

Originally designed for corrosion monitoring of boiler membrane walls, systems can be used for a range of applications, such as pipes and storage vessels. In the case of membrane walls, sensor locations are typically spaced 1-2 meters apart and arranged in rows and columns to form two dimensional sensor arrays. During the scanning process, current is passed horizontally, diagonally and vertically between adjacent sensor locations. Current flows through both fire-side and cold-side tube walls, with freedom to spread out on its journey between current source and sink.



DC Current flows through the Whole Tube Cross Section

As the fire-side tube wall thins due to corrosion, the measured resistance increases and this is translated into metal loss and corrosion rate. Corrosion is calculated assuming 'uniform' metal loss between adjacent sensor locations.

HFC monitors use similar measurement principles but provide more focussed monitoring of both corrosion and heat flux, typically across a single tube on a boiler membrane wall.

High and dynamic temperatures experienced by tube membrane walls invariably produce some degree of background thermal 'noise' on the measured signals. A small amount of electrical interference may also be present, especially if high-power cables are nearby. For these reasons, our boiler monitoring systems operate on a continuous basis and measurements are made several times a day. This allows any effects due to temperature variations or electrical interference to average out over time so that underlying trends due to corrosion can be detected and quantified.

Corrosion Probes

RTL's variable-temperature ER (VTER) corrosion probes are typically used to continuously monitor superheater and reheater corrosion in power generation boilers, but can also be used for other applications. They have a corrosion element, in the form of a disc or tube, mounted at the probe tip. Cooling air maintains the element at a pre-set temperature.

ER measurements monitor thinning of the elements: For tubular elements, electrodes pass current between the tube ends, the current rapidly spreading throughout the tube body. Circular elements have electrodes welded to the rear face. Elements are typically less than 2mm thick and current flow is highly constrained, so measured signals are considerably higher than those from a membrane wall.

Tubular Probe Elements:

Periodic Monitoring – RTL's Portable Scanner Systems

RTL's Portable Scanner

These have been developed for applications where continuous monitoring, using permanently-installed systems, may not be appropriate. An example may be when monitoring at a number of different locations within a large production or process plant.

The system operator periodically returns to the same site location, comparing data between visits, to determine if any physical changes have taken place, for example, when looking for signs of crack growth at a pipe joint.

The latest 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 (in a similar fashion to our fixed scanners).

When performing periodic monitoring, factors that might influence the measurements need to be considered:

Electrode Spacing: Consistency in electrode position, between measurements, is important: this is one reason why RTL normally uses fixed, welded sensors. If welded sensors are not an option, then it may be practical to press electrodes against the surface using specially-designed jigs. Consistency of position can be aided using washers attached to the metal surface.

Temperature: We have already considered options for compensating for the effects of temperature. Accurate measurement of surface temperature requires the use of thermally-bonded temperature 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.

‘One-Time’ Surface Inspection

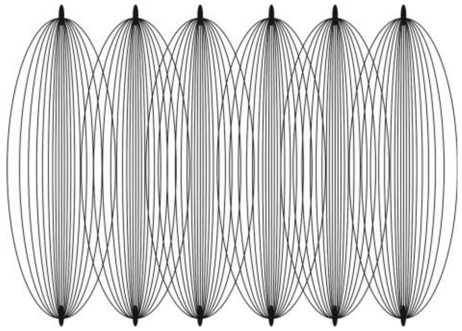
So far, we have discussed the use of systems to monitor changes in surface conditions by examining trends in ER measurements over time. Under certain conditions, it might be feasible to use DC ER measurements to directly detect the presence of defects as electrodes are moved along a surface.

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 variations in voltage gradients across the surface and so may confuse the readings.
- Move the voltage electrodes across the surface, monitoring changes in voltage that might indicate the presence of a defect. The spacing between the electrodes should be fixed at all times - variations in spacing will have a direct effect on measured voltage.

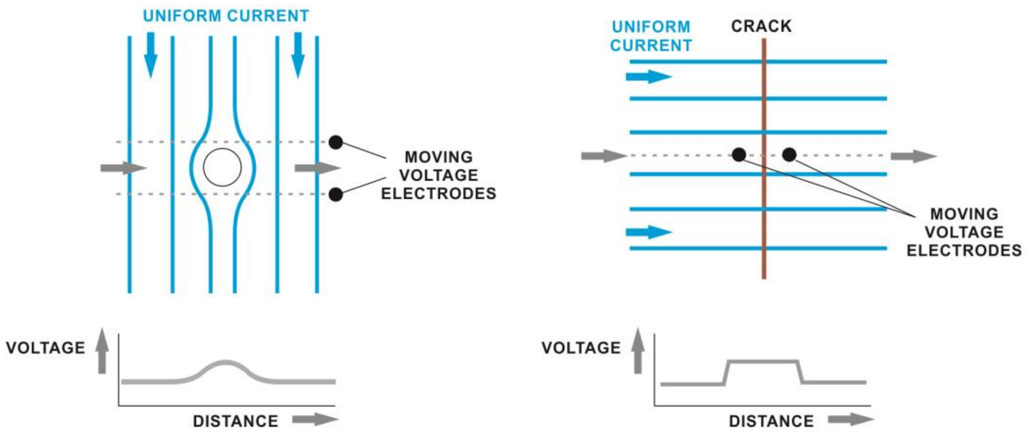
Current Density: Creating a uniform current density along a surface is more straight-forward for some applications than for others. Earlier we discussed how surface boundaries ‘force’ the current to flow in a particular direction: in the case of a pipe, assuming sufficient distance between current source 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, as shown here.



A ‘Current Curtain’ using Multiple Current Sources and Sinks

The examples below show how the technique might be used in practice for detecting pits and cracks:



The Effect of a Pit (Left) and Crack (Right) on Measured Voltage using Moving Voltage Electrodes

With care, signal 'amplification' might be achieved by locating current electrodes in close proximity to the voltage electrodes and then moving all electrodes over the surface. This produces a high and consistent current density in the vicinity of the voltage electrodes, so amplifying the voltage signals.

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: Signal changes caused by a defect must be greater than any changes due to non-uniformity in wall thickness produced during manufacture. In other words, the more uniform the original surface thickness, the better the chance of identifying a defect.

Temperature: Uniformity of temperature will help optimise measurement quality.

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.

In Conclusion

When applying ER measurement techniques, different circumstances require different approaches to the technique employed, and factors that might influence measurements need to be considered.

Understanding the behaviour of current flow through metal surfaces, the effect of surface temperature changes, and being aware of the operating environment with regards to possible electrical interference, all help the user to optimise the measurement process to maximum effect, within a range of applications.