Towards The Resolution Of Discrepancies In The Measurement Of Low Frequency Electrical Conductivity Used For Non-Destructive Testing

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Abstract

A good example of the need for interoperability of measurement standards exists in the field of electrical conductivity of non-ferrous metals and alloys. This measurement is of particular interest to the aerospace industry and to the coin production and handling industries as it provides a measure of the quality of parts. These industries use commercial conductivity meters which measure the parameter using an AC technique. Traceability to national standards in many countries, including USA, is achieved using DC measurement techniques, although the UK's National Physical Laboratory (NPL) has an established method for achieving this traceability by an AC technique. Due to the effects of frequency and the behaviour of the materials used as reference standards, there can exist discrepancies between the AC and DC techniques.

This paper describes a project aimed at addressing these discrepancies being undertaken by a consortium of partners and funded by the European Commission's Framework 5 Programme on Competitive and Sustainable Growth. The partners are 3 national metrology institutes (NPL (UK), PTB (Germany), NMi (Netherlands)), 2 European instrument manufacturers in this area (Hocking NDT Ltd (UK), Institut Dr Foerster (Germany)) and a representative of the aerospace industry (EADS Launch Vehicles).

1. Introduction

Eddy current conductivity measurements are used as a routine inspection method for vast quantities of aluminium alloys used in aircraft manufacture. The relationship between the mechanical hardness and the electrical conductivity of individual alloys has been well established. Thus for the aerospace industry, conductivity measurements form a very important quality assurance which is directly reflected in the safety of an aircraft.

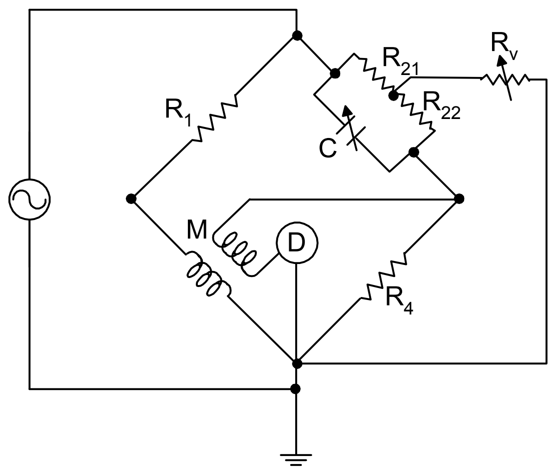
The majority of conductivity reference standards produced by manufacturers of eddy current conductivity meters are traceable through conductivity standards measured using a direct current method[1]. This would be a satisfactory situation if the materials had uniform properties throughout their thickness. Most of the reference standards produced in this way for the aerospace industry are special alloys of aluminium which undergo grain stretching and precipitate hardening processes. In many cases the finished material has different conductivity values in the surface layers to that of the bulk of the material. Since many commercial eddy current conductivity meters operate at a frequency of 60 kHz and above, the penetration depth of the eddy currents is only a few millimetres at most. Reference materials produced by NPL and calibrated at a frequency of 60 kHz with traceability to electrical standards are used in the major European aerospace standards laboratories but traceability to other European national metrology laboratories is to a DC method. However, due to the need to intercompare with US manufacturers who are believed to use reference standards also measured by the DC method, it is necessary to investigate how well the two methods of measuring conventional aluminium alloys agree and how well industrial partners agree with recognised national metrology laboratories.

The work in conductivity has recently assumed a greater importance within Europe due to the introduction of the new euro coinage with emphasis on detection and fraud prevention. This research includes work on a specific conductivity value of interest to the coin production and handling industries.

The project has reached approximately its midpoint and work to date has mainly been undertaken by the national metrology institutes. The contribution by the industrial partners will begin in the second half of the project. The work is progressing in 2 ways. A methodology is being developed to improve the traceability and reliability of measurements and to exploit a technique with potential to become the basis for a new measurement method of industrial importance. The development of this method, based on the van der Pauw principle, is examining the applicability of the method at both DC and AC. Work is also being undertaken on using an alloy of copper and germanium, not previously used in this field, as a new reference material for conductivity which may remove the difference between existing AC and DC techniques. One advantage of the chosen alloy is the ability to tailor its conductivity value to the required value. Conventional alloys are also being investigated.

2. Existing methods of measurement

Prior to this work, some of the national metrology institutes involved had established methods for conductivity measurements. Two techniques are used. NPL uses a modified Heydweiller bridge normally working at a frequency of 60 kHz, but capable of working in the range 10 kHz to 100 kHz, and shown in Figure 1.



R_v = variable resistor

C = variable capacitor

$R_{21} = R_{22} = 10\ k\Omega$

$R_1 = 1\ k\Omega$

$R_4 = 10\ \Omega$

M = toroidal mutual inductor

Figure 1. Modified Heydweiller bridge for measurements at 60 kHz.

The bridge measures the change in mutual resistance of a toroidal mutual inductor when a ring of non-ferrous metal is introduced into the toroid [2, 3]. From this measurement the conductivity of the metal can be calculated, but this is a complex procedure and many correction terms are needed. Consequently this technique has not been adopted in other national metrology laboratories.

NPL, PTB and, now, NMi have a DC technique where the conductivity is measured on metal bars as shown in Figure 2. The current is introduced into the bars using specially designed clamps. The voltage is measured between two knife-edges, the distance between which is accurately known. The cross-sectional area of the bar must also be determined. This is an established technique but is challenging as the voltages to be measured are small and require nanovolt resolution, for currents which do not introduce significant heating.

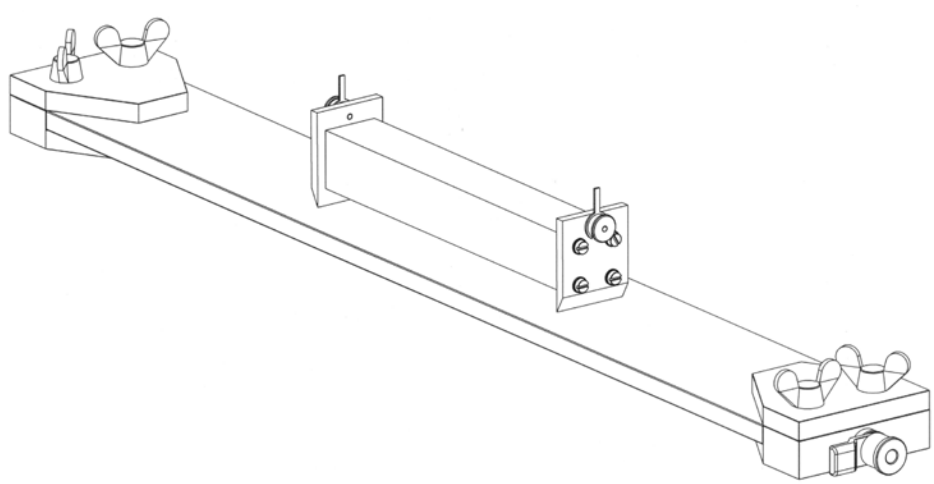


Figure 2. Sketch of a bar-shaped conductivity sample, showing clamps for introducing the current and knife edges for voltage sensing.

It has become apparent that laboratories taking their traceability from these two techniques can have commercial conductivity meters which do not agree when used to measure the same metal or alloy. The agreement between the two techniques also changes for different materials. Clearly this is not an ideal situation and will certainly not be restricted to the laboratories involved here.

3. Development of the van der Pauw technique

The work aims to investigate a new and simplified measurement technique based on the van der Pauw technique[4, 5] which may

- either have application in both AC and DC measurements
- or help to establish agreement between DC and AC techniques.

The three national metrology institutes have developed DC measurement systems based on this technique[6].

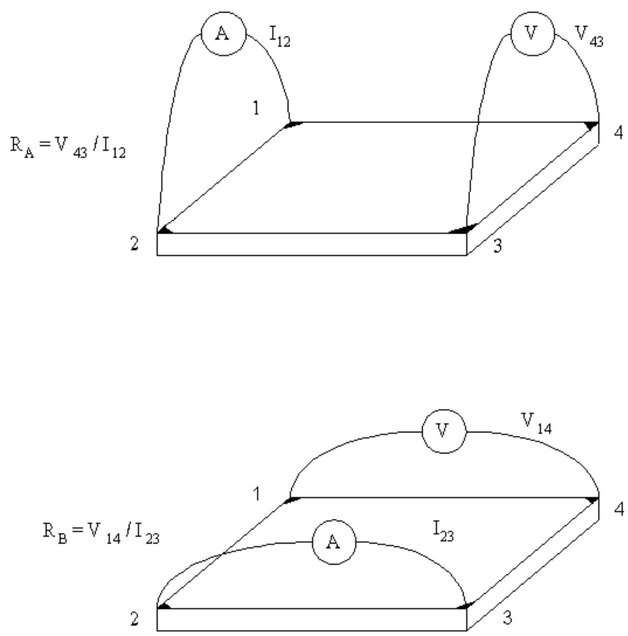


Figure 3. The van der Pauw geometry.

The van der Pauw technique is essentially a four terminal resistance measurement. Considering a rectangular test specimen of constant thickness, four contacts are made around the perimeter. The van der Pauw theory requires these contacts to be small compared to the in-plane dimensions. Labelling these contacts as shown in Figure 3, the resistance values shown obey the relationship:

$$\exp(-\pi R_A/R_S) + \exp(-\pi R_B/R_S) = 1 \qquad (1)$$

where R_S is the required resistance.

If the two measured resistance values R_A and R_B are similar, this can be written as

$$\frac{1}{\sigma} = \frac{\pi d}{\ln 2} \frac{(R_A + R_B)}{2} \qquad (2)$$

where d is the thickness in m and σ is the required conductivity in S/m.

If the contacts have a finite size an error can be introduced. The magnitude of this error depends on the relative dimensions of the contact area and the test specimen in-plane dimensions.

It was preferred to use square block-shaped reference samples as these had already found application as reference samples from the established AC technique. To determine if the contact geometry to be used for a block introduced an error in the measurement of conductivity, a test specimen in the shape of a star was engineered. With this geometry, the necks of the star guide the current into the central area to produce the required current distribution and the size of the electrical contacts is not important. A test specimen with the theoretically-required star geometry was produced from the same alloy as existing blocks and bar. The star geometry is shown in Figure 4.

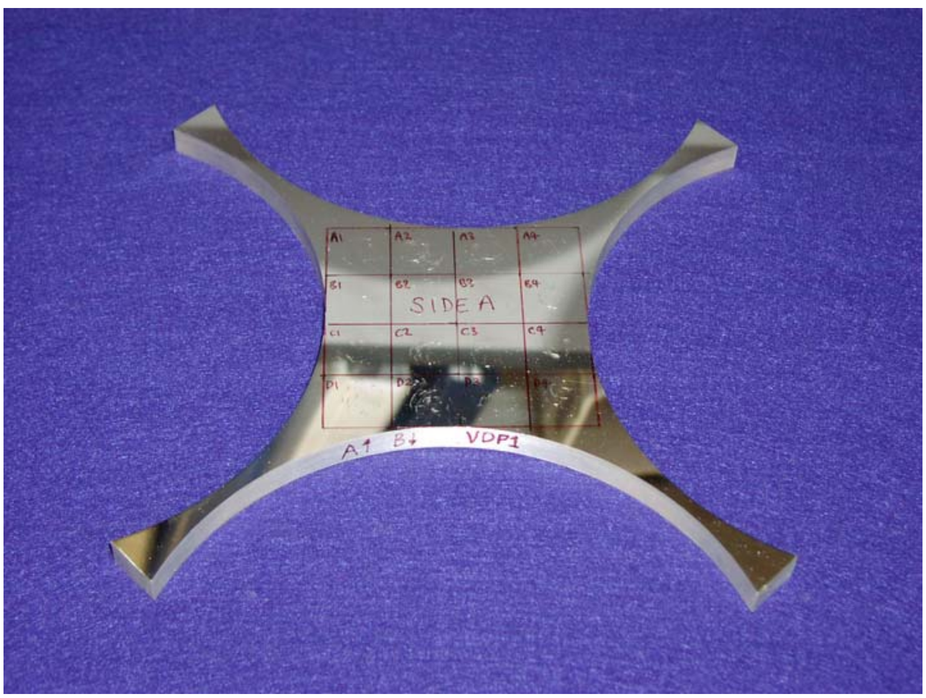


Figure 4. The star geometry.

One possible design for the clamps to the block corners is shown in Figure 5. In this particular example four brass blocks make contact to the corners of the sample, which lies in the middle of the plastic holder. Two of the brass blocks can be screwed inwards in order to clamp the sample on all edges, achieving a typical contact resistance of a few mΩ.

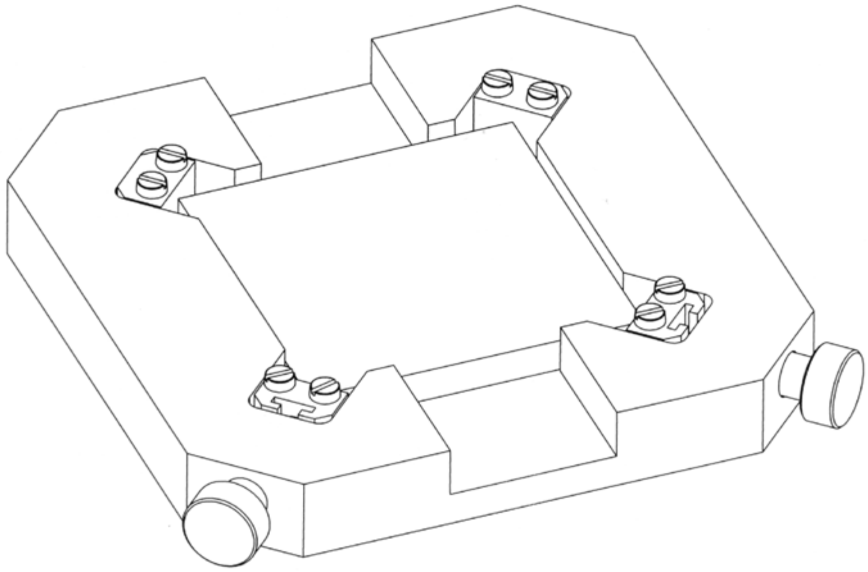


Figure 5. Sketch of a possible clamping arrangement for square conductivity samples.

4. Preliminary comparison of van der Pauw DC measurements

Shown in Table 1 is a summary of the DC conductivity values measured by NPL, PTB and NMi on three aluminium blocks made from the same sheet. Also shown are the measurements made at NPL on the star geometry also made from this sheet.

Table 1. DC conductivity results.

Institute	Block No.	DC conductivity (MS/m)	DC Conductivity of star (MS/m)	Estimated Uncertainty (95%) (%)	Difference from average (%)	Combined uncertainty (95%) (%)
NPL	21	35.795	35.786	0.15	-0.096	0.236
PTB	23	35.815	-	0.06	-0.040	0.175
NMi	24	35.878	-	0.20	0.136	0.280

NPL measurements on the block and the star agree within the measurement repeatability. The adopted contact and test specimen geometries can therefore be used without introducing significant errors.

It can be seen that there is agreement well within the estimated uncertainties between these laboratories for these preliminary measurements. This is a good starting point from which to explore further the historical differences between other techniques.

5. Reference materials

The range of values being examined for this work is from 2 to 59 MS/m.

The techniques discussed require a variety of different shapes of reference standards, although the partners in this work have agreed to work with a sample thickness of 10 mm. The modified Heydweiller bridge uses toroidal samples of 380 mm outer diameter and 220 mm inner diameter. The bars used in different laboratories are up to 600 mm long by up to 80 mm wide. The van der Pauw star has a maximum linear dimension of 250 mm and the blocks are 80 mm square.

One of the objectives of the project is to establish the agreement between existing and new DC and AC methods of conductivity measurement. As the different methods need samples with different geometry, the best way to check the consistency of the results obtained by the different methods is to prepare the samples from the same metal or alloy plate. As a prerequisite the plate has to be homogenous.

The work is examining conventional materials, and alloys such as aluminium, aluminium alloys, Nordic gold and titanium are being used. It is also aiming to produce a new generation of reference standards based on an alloy of copper and germanium where the quantity of germanium can be adjusted to tailor the value of conductivity. One possible reason for a disagreement between DC and AC methods is due to surface properties of the materials used for standards. It is hoped to test this possibility with the copper germanium alloy.

6. Future work and conclusions

A future stage in this work will involve the participation of the 3 industrial partners. It is clear that their requirements for reference standards will be different from those of the national metrology institutes and it is yet to be seen whether a new generation of reference standards can find application with them.

The work of the national metrology institutes is also continuing. NPL and PTB will be examining the van der Pauw technique to assess its usefulness in different frequency ranges up to 100 kHz, which is the lowest operating frequency of the commercial conductivity meters. There will be significant challenges in this work and the way forward may either be in the application of the developed systems for AC measurements, or a series of adjustments to DC values may be obtained by a comparison of the van der Pauw technique with the AC technique.

A major factor in the future of the work addressing the agreement between AC and DC conductivity measurement techniques must be discussions between users, metrology institutes and standards authorities. Existing written standards, such as [1], prescribe routes for traceability which may need to be examined in the light of the present work. The aerospace industry is particularly international in nature and these discussions must involve interested parties in Europe, US and beyond.

At the start of this work the partners were aware of the issues in the aerospace industry but have become increasingly aware of the issues in the coin production and handling industries. It is planned to hold a workshop to examine and address the problems encountered in this area within the next year.

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