EXPERIMENTAL CHARACTERIZATION OF OVERHEAD ELECTRICAL LINE CONDUCTORS AFTER ANODIC OXIDATION

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ABSTRACT
The paper reports detailed descriptions and discussions of the carried out activity aimed realizing and verifying the performances of anodised aluminium conductors with increased emissivity and reduced absorptivity coefficients. In particular measurements of emissivity coefficients, and thermal, mechanical and electrical properties in function of the loading current were carried out for different types of anodised elementary wires. Environmental accelerated ageing tests and fatigue mechanical tests were also performed.

INTRODUCTION
The temperature of overhead transmission line conductors (and consequently the relevant transmission capacity) is limited, since it produces ageing of the materials and gives rise to elongation of the conductor with consequent reduction of the clearances to ground.
In its turn conductor temperature depends on one side from the properties of the materials, from the dimensions and from absorptivity and emissivity coefficients and on the other from meteorological conditions (ambient temperature, wind velocity and direction, solar radiation).
The modification of emissivity coefficients may sensibly increase the power dissipated by radiation and allow an increase of transmission capacity. So far this modification has been obtained by mechanical treatments of the surface or by deposition of lacquer and varnishes (“coloured”, that requires particular attention during installation and may be removed with time).
In last years the setup of process parameters and of the dipping procedure in aluminium anodising treatment has allowed to obtain pieces with very high emissivity coefficients, highly protected against corrosive attacks.
With the aim to verify the performances of anodised aluminium conductors, CESI RICERCA, in the frame of a Public Interest Energy Research Project named “Ricerca di Sistema” supported by MSE (Italian Ministry for Economical Development), carried out an experimental activity aimed at defining appropriate anodization treatments in order to obtain elevated values of emissivity coefficients, together with reduced values of absorptivity ones.

ADVANTAGES OF ANODIC OXIDATION
As above mentioned the anodization process allows a sensible increase of the emissivity coefficient, as for coloured conductors, but differently from them, where the absorption coefficient is high and almost equal to emissivity, it allows (by the process of “brightening”) to obtain a reduced value of absorption coefficient.
In case of coloured conductor the advantage in terms of increased capacity becomes evident, with respect to traditional ones, for temperature above 60 -70° °C: at this temperature the energy emitted by radiation (function of the difference between absolute conductor temperature and absolute ambient temperature elevated to the fourth) is greater than the energy absorbed by sun radiation.
In case of the anodized conductor the aim is to reduce (by “brightening” of the anodized layer) the above temperature to less than 30°-40° C, and thus obtaining advantages not only for high temperature conductors but also for standard ones. Moreover the anodization treatment produces a stable layer, resistant to environmental stresses and mechanical abrasion.

ANODIZATION PROCESS
Anodization represents a well known industrial process for the finishing of aluminium products.
Figure 3 reports a scheme with the main treatments involved in an anodization process.

Figure 1 - General scheme of the anodization process.

By means of contacts with the Italian association for surface aluminium treatments (AITAL), it was possible to find a company (l’Anodica of Cologno Monzese) specialized in chemical and electrochemical surface treatments, and
discuss with them the different possible passages to obtain the desired results (high emissivity and low absorptivity coefficients) for the treatment of conductor surface.

ANODIZATION OF THE SAMPLES

As a first attempt it was decided to realize four different samples of elementary wires adopting different technologies for colouring and sealing: three samples had a black/bright surface (samples N1, N2 and N3) and one a brown/bright one (sample M).

In particular samples N1 and N2 were subjected to colouring by absorption, and samples N3 and M by electro colouring in Sn salts.

Subsequently sample N1 was subjected to a sealing process at high temperature while samples N2, N3 and M had a sealing at ambient temperature.

All the samples were subjected to chemical brightening.

Fig. 2 reports a view of the anodized samples together with the standard one (without any treatment).

Figure 2 – View of the elementary wires samples.

MEASUREMENTS AND TESTS

Cross sections of anodised elementary wires were then analysed by SEM (Scanning Electron Microscope) in order to measure the thickness of the anodic layer, to assess its uniformity and the possible presence of localised defects.

Fig. 3 reports the SEM picture of one of the sample subjected to electro-colouring, in which it is evident the presence of a thin layer of SnO₂ (~ 2÷3 μm), at the interface Al bulk-Al₂O₃ layer, used to obtain the range of colours from bronze to black.

Table 1 reports the thickness of the anodised layers measured on the four samples (the electro-coloured samples, N3 and M, show higher thicknesses, due to the SnO₂ layer).

Moreover by means of EDS technique (Energy Dispersion X-ray Spectroscopy) it was possible to characterize the composition of the layer.

Table 1 – Thickness of the anodised layers

<table>
<thead>
<tr>
<th>Sample</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
<td>Brown</td>
</tr>
<tr>
<td>Thickness (μm)</td>
<td>15.61</td>
<td>16.07</td>
<td>18.65</td>
<td>19.06</td>
</tr>
</tbody>
</table>

Figure 3 – SEM picture of the cross section of N3 sample

Figure 4 reports the EDS results of the sample N3. Its powder contains:

- ~95% of Aluminium, mainly due to the bulk material of the wire, with a contribute of the anodic layer,
- 4% of Oxygen coming from the anodic layer,
- ~ 1% of Sulphur and Tin, the former originated by a residual of the H₂SO₄ used in the anodizing and the latter coming from the SnO₂ layer.

After the dimensional and composition verifications, the elementary wires were subjected to the tests prescribed by national and international standards and to tests aimed at verifying the anodised layer withstand to static and dynamic bending (Figure 5). In particular an alternate bending test was carried out in order to verify the fatigue withstand of the anodised sample in comparison with the bare standard wire.

The results of the test showed that the anodised samples had a better performance than the standard one (the breakages occurred after more bending cycles).

The samples were also subjected to accelerated environmental ageing tests, with solar radiation, humidification, aspersion with demineralised water, immersion in acid solution, thermal cycles.
One of the samples (M) showed marked circumferential lines on the surface, due, as from discussion with AITAL experts, to the excessively aggressive acid solution used (we adopted, in a conservative way, the same pH we use for plastic materials).

**Figure 5** – Tests of static and dynamic bending.

The assessment of the emissivity ($\varepsilon$) and absorptivity coefficients ($\alpha$) was then carried out by means of special test set-up realized for the scope. In particular in order to evaluate the absorptivity coefficients a special set-up (with the use of lamps reproducing the solar spectrum) was designed in order to have a very high uniformity of the radiation on the samples under test (Figure 6).

**Figure 6** – Simulation of the spatial distribution of the radiation produced by the arrays of lamps.

Figure 7 reports the test set-up realised on the base of the above computer simulation. The disposition of the samples and of the arrays of lamps is inclined (almost vertical) in order to avoid the possible influence of air convection generated by the lamps on the elementary wires.

In this way it was possible to estimate the absorptivity and emissivity coefficients by using a thermal model derived from the CIGRE one and calibrated on the base of long duration measurements on experimental spans [1].

**Figure 7** – View of the test set-up for the measurements of the absorptivity coefficients.

The results showed that the black samples had emissivity in the range of $0.9 \div 1$, the brown sample of about $0.8 \div 0.9$ and the standard one of about $0.4$.

As regard absorptivity samples N3 and M showed values close to 1, N1 and N2 values around $0.7 \div 0.8$, while the emissivity coefficient of the standard bare elementary wire was about $0.4$.

The emissivity coefficients were also confirmed by means of measurements carried out by a special high speed thermo camera using a "reference emittance" technique (figure 8).

**Figure 8** – View of the test set-up for measuring emissivity coefficients by “reference emittance” technique

On the base of these results and with the aim of a further reduction of the absorptivity coefficients, it was decided to realize other samples without any pigments for colouring.

Two other samples were then realized:

- Bright (Bri) – obtained by colourless anodic oxidation over a mirror-like surface by brightening;
- Opaque (Opa) - obtained by colourless anodic oxidation without brightening.

Table 2 summarizes the results of the emissivity and absorptivity tests. As it is possible to see the sample “Bri” shows the highest value of emissivity and smallest value of absorptivity (0.27), even less than that of standard bare wire.
Table 2 – Emissivity and absorptivity coefficients of the tested samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\alpha$</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>$Bri$</td>
<td>0.27</td>
<td>~1</td>
</tr>
<tr>
<td>$Opa$</td>
<td>0.36</td>
<td>0.94</td>
</tr>
<tr>
<td>$N1$</td>
<td>0.7±0.8</td>
<td>~1</td>
</tr>
<tr>
<td>$N2$</td>
<td>0.7±0.8</td>
<td>0.9±1</td>
</tr>
<tr>
<td>$N3$</td>
<td>~1</td>
<td>0.9±0.96</td>
</tr>
<tr>
<td>$M$</td>
<td>~1</td>
<td>0.8±0.9</td>
</tr>
</tbody>
</table>

As an example during the heating test with a current of 100 A, the above anodized sample reached a temperature of 115 °C while the standard one reached a temperature of 170°C.

Again, from simulations, if we consider a conductor with a diameter of 31.5 mm with the external layer made of these elementary wires in presence of a solar radiation of 1000 W/m², an ambient temperature of 30°C and a very low wind (0.05 m/s) with a current of 1500 A, we would have a temperature of 135°C compared to 190°C of the standard bare one.

On the base of the analyses carried out at SEM and from bibliography [2] these high emissivity and low absorptivity values of the bright uncoloured sample ($Bri$) are due to the fact that the anodized layer tends to be transparent to solar radiation, which is reflected by the underlying brightened surface. While in the infrared field the emission by radiation is very high thanks to the pores of the anodized layer. Moreover the brightening process reduced the dimension of these pores, thus allowing a higher emissivity of this sample with respect to the opaque one ($Opa$).

Other bright uncoloured samples were produced with different thickness in order to verify the sensitivity of the $\varepsilon$ $\alpha$ coefficients to this parameter.

These coefficients showed no modification till a thickness of 4 $\mu$m, while a sample with 2 $\mu$m of anodised layer showed a very low coefficient of absorption (0.2) but also a very low emissivity coefficient (0.3).

**REMOVAL OF ANODISED LAYER**

Before the conductor realisation some tests were made on the black coloured samples to verify a procedure to remove the insulating anodic layer. This is necessary to obtain a good electrical contact between the conductor and the clamps or joints in a overhead line. A chemical treatment was set-up, using a basic solution of NaOH (50g of the base into a litre of water to obtain a pH=14) in a temperature range from 50°C to 60°C. For the wires ~ 50 s were sufficient for a complete removal of the layer. After the treatment a good rinsing in running water lets the solution residuals to be eliminated.

Figure 9 shows the comparison among a standard wire and the anodised samples at the end of the anodic layer removal.

**CONDUCTOR REALISATION**

On the base of these results it was decided to adopt this technique of anodic oxidation to realize the outer layer of an ultra compact TACSR conductor [3] produced by De Angeli company. Figure 10 reports the drawing of the cross section of the conductor.

Figure 10 – Cross section of the ultra compact TACSR conductor chosen for anodic oxidation

Figure 11 shows some phases of the realization of the conductor at De Angeli factory. As can be seen from the picture the appearance of the realized conductor is similar to the bare conductor without treatments.

Figure 11 – Stranding of the ultra compact TACSR.

Samples of conductor were then tested on short spans in CESI RICERCA mechanical laboratory in Brugherio. Tests were carried out in presence of different values of simulated solar radiation and/or of currents.
Figure 12 shows the test set-up, with an array of lamps for reproducing the solar radiation.

![Image of test set-up](image)

**Figure 12 – Test set-up for reproducing the solar radiation on the conductor.**

From the first carried out tests there is the confirmation of the very low values of absorptivity coefficient (less than that of the bare conductor) and of the very high values of emissivity coefficient. As an example Figures 13 and 14 report respectively the temperature rise of standard bare and anodized conductors for a same (medium-high) solar radiation and for different values of current.

![Image of temperature rise](image)

**Figure 13 – Temperature rise of standard bare and anodized conductors for a same (medium-high) solar radiation.**

![Image of temperature rise](image)

**Figure 14 – Temperature rise of standard bare and anodized conductors for different current values.**

**CONCLUSION**

The growing demand of electric power requires a continuous increase in the power transferred by electrical lines. The modification of emissivity and absorptivity coefficients of conductors may sensibly increase the power dissipated by radiation and allow an increase of transmission capacity. Colourless anodic oxidation plus brightening proved to be a very stable and resistant mean of sensibly increasing emissivity (close to 1) with at the same time reduced values of absorptivity (less than that of the bare conductor).

**REFERENCES**


**Acknowledgments**

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