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Experimental developments in metal sheet used as natural air-termination system

Sueta, H.E Caires, L.E Shigihara, M. Silva Neto, A.
Instituto de Energia e Ambiente
Universidade de São Paulo
São Paulo, Brazil
sueta@iee.usp.br luis@iee.usp.br mshigi@iee.usp.br
acacio@iee.usp.br

Ruiz Munoz, D. Rodrigues, M. A.
AT – Lightning and Earthing Research Center
Parque Tecnológico de Valencia
Valencia, Spain
druiz@at3w.com manuelantonio@at3w.com

Abstract- This paper presents some experimental developments in metal sheets used in metal roofing as part of the natural air-termination system. The compositions of the samples tested and the results of the current tests simulating the continuing currents and with impulsive currents are analyzed.

Keywords-LPS, metal tiles, natural air-termination system, lightning perforations

I. INTRODUCTION

Metal roofs can be used as a part of an air-termination system. In order to do this, they must comply with the requirements described in IEC 62305-3: 2010 [1], especially those described in Table 3 which provides "Minimum thickness of metal sheets or metal pipes in air-termination systems".

As the table in the standard lists only the thicknesses for lead, steel (stainless, galvanized), titanium, copper, aluminum and zinc, in the case of metal alloy tiles and coated tiles, the thickness to be used is uncertain. In fact, almost all of the metal tiles are not built with pure materials plates according to the Table VI presented in this paper, but they are alloys or are coated with another material.

This paper presents some results of tests performed on sheet metal, with the objective of comparing the results of the different sheets and estimating suitable thicknesses for the metal alloy sheets.

The plates in question are those to be used in buildings where it is not important to prevent perforation, the generation of hot spots will not cause damages or may cause fires or explosions or some kind of ignition (thickness *t*' of annex Table VI as presented in this paper).

In this study, the focus was to analyze the composition of some metal tiles and verify the perforations in tests with DC pulses simulating the continuing currents and tests with current impulses (10 / 350µs waveform). Future work will examine other aspects such as the ability to conduct lightning currents, the effects of these currents on connections and joints, etc.

II. EXPERIMENTAL DEVELOPMENTS

A. Identification of samples and tests

In order to initiate the experimental tests, 46 samples were prepared: 10 samples of metal alloys identified as Galvalume; 10 samples of metal alloy tiles identified as IEE ALLOY; 8 plate samples identified by the manufacturer as aluminum, and 18 plate samples indicated by the manufacturers as Zinc (9 of nominal thickness of 0.5 mm and 9 of nominal thickness of 0.65 mm).

Most of the samples are sheets or pieces of metal tiles of dimensions 0.50 m x 0.50 m (Samples tested at USP) and others of dimensions 0.20 m x 0.20 m (Samples tested in Spain).

Initially the thicknesses of all the samples were measured using a micrometer in 4 points, the thickness being considered the average of these points.

Some samples of dimensions 0.50 m x 0.50 m were submitted to tests with DC pulses simulating continuing currents. Pulses with approximately 100, 150, and 200 C with tolerance of ± 20% were applied according to Table C.2 of the Brazilian standard [2]. These tests were performed at the High Power Technical Service of the Institute of Energy and Environment of University of São Paulo.

Some samples of dimensions 0.20 m x 0.20 m were subjected to tests with impulsive currents to simulate the first positive pulse with 10 / 350 µs waveform and peak values of 100, 150, and 200 kA. These tests were carried out at the AT - Lightning and Earthing Research Center, in the Technological Park of Valencia, Spain.

After the tests, samples from No. 7 (Galvalume); No. 18 (IEE ALLOY); No. 24 (Aluminum); No. 31 (Zinc 0.5 mm) and No. 40 (Zinc 0.65 mm) were analyzed in the Laboratory of Technological Characterization of the Polytechnic School of University of São Paulo in order to verify the composition of these tested samples.

B. DC pulses tests

The test consists of applying DC pulses simulating continuing currents in metallic plates under controlled conditions.

The test setup is showed in Figure 1.

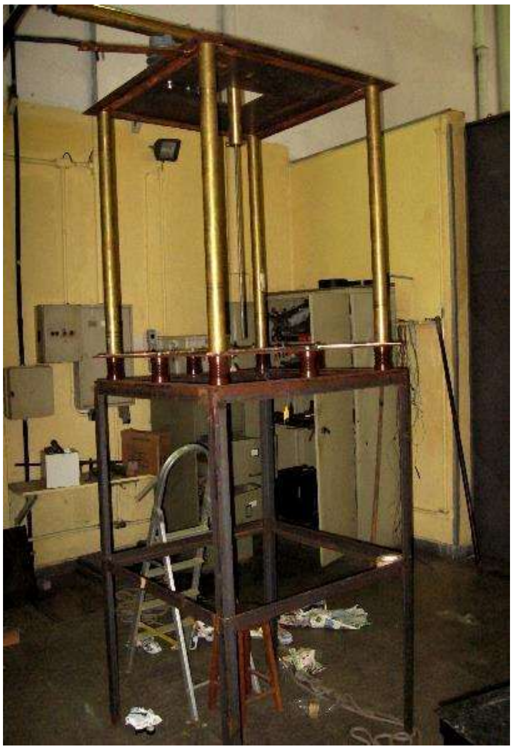

Figure 1 - Test setup - test of DC pulses simulating continuing currents.

As shown in Figure 1 there is a central electrode (rod) which by convention of the figure was indicated as the negative and the base electrode where the plate under test was installed in the convention of the indicated Figure as the positive. In the test, effectively the polarity applied was opposite to the convention and the central electrode was connected to the positive of the DC source and the plate under test was connected to the negative.

The variation of the applied load was obtained by varying the duration of the application.

The control parameters for each test were:

- arc current;
- application duration;
- wear on the plate.

The tests were performed by using a power source, a 3 MVA transformer, 13800 / 760-440-380-220 V, primary adjustable in ± 18%, 6%, 60 Hz, 3-phase steps connected to a bridge three-phase rectifier as shown in Figure 2.

The DC current was measured by shunt resistor and a digital oscilloscope (digital scope DL850), manufactured by YOKOGAWA.

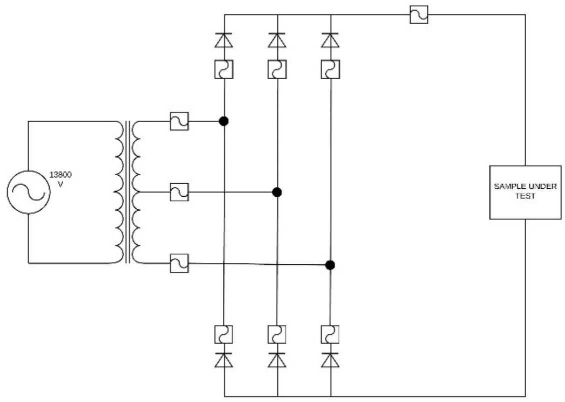

Figure 2 – Illustrative circuit of three-phase rectifier bridge used in the DC tests.

DC pulses simulating continuing currents (as shown in Figure 3) used to verify the thermal effects were applied directly to the plates with an approximate 2 cm gap and a small copper wire were connected between the rod and plate used to initiated the electric arc.

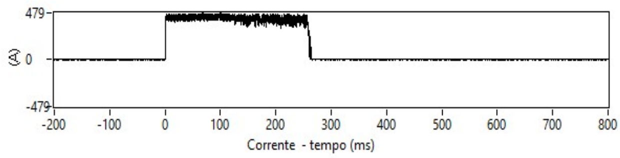

Figure 3 - Example of applied DC pulse oscillogram obtained in the tests.

Concerning DC pulse tests the following parameters were recorded for each application: current (A), time duration (ms), charge (C), and average perforation diameter (D).

C. *Impulsive currents tests*

Current impulse tests were performed at the AT-Lightning and Earthing Research Center in Valencia, Spain.

As a test source, a current impulse generator, as shown in Figure 4, was used that allows peak currents of up to 320 kA and a waveform of 10 / 350 μs in crowbar mode configuration. The pulse current measurement was performed by a Pearson model 1330 current sensor, certificated by SIMT (Shanghai Institute of Measurement and Testing Technology).

Figure 5 shows the arrangement used for current impulse applications and Figure 6 shows an example of an applied impulse.

Figure 4 - Setup for tests with current impulses of 10/350 μs.

Figure 5 - Arrangement used for tests with current impulses.

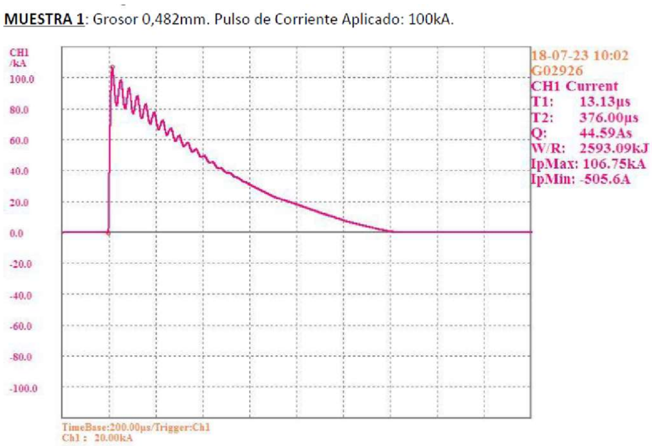

Figure 6 - Example of applied current impulse.

For the different type of samples, pulses of 100 kA, 150 kA and 200 kA were applied. For each application, the peak current (kA), the charge (C), the specific energy (kJ / Ω), and the state of the sample (deformed or perforate) were recorded and/or calculated.

D. Characterization of sample materials

Samples of the 5 types of metal plates (3.5 cm diameter disk samples) were sent to the LCT - Technological Characterization Laboratory of the Polytechnic School of the University of São Paulo to characterize the sample materials.

Two different techniques were applied for the characterization of the samples: one type of sample one was more representative; and the other technique provided more coherent results.

In the sample called “galvalume”, the contents were determined by quantitative analysis in samples prepared by digestion with royal water and dosed in an optical emission spectrometer (ICP OES), brand Horiba, model Ultima Expert. This sample, called “galvalume”, was obtained in sample Nr. 07, presenting: 3.57% of aluminum; 93.1% iron; 0.221% manganese; 2.34% zinc, 0.0036% calcium; 0.01% phosphorus; 0.0068% sulfur; and 0.026% silicon.

In the other samples, the contents were measured in a standardized sample of the STD-1 (Standardless) calibration, on the non-standard analysis of the chemical elements between fluorine and uranium, in a Malvern Panalytical X-ray fluorescence spectrometer, model Zetium. Values were normalized to 100%. The Fire Loss (PF) was performed at temperature of 1020 °C for 2h.

The sample called “IEE Alloy” showed the following quantity: aluminum 42.6%; zinc 38.3%; iron 17.2%; silicon 0.98%; phosphorus (0.17%); sulfur (0.35%); chlorine (0.07%); potassium (0.04%); calcium (0.02%); titanium (0.02%); chromium (0.06%); manganese 0.02%); and nickel (0.01%).

The sample called aluminum showed an amount of 98.3% aluminum, but also consists of small amounts (<1%) of sodium, manganese, silicon, phosphorus, sulfur, chlorine, potassium, calcium, titanium, vanadium, manganese, iron, nickel, gallium, zirconium, and lead.

Samples called “Zinc1” (0.5 mm) and “Zinc2” (0.65 mm) showed an amount of aluminum (40.9% in Zinc1 and 43.4% in Zinc2); iron (16.7% in Zinc1 and 13.4% in Zinc2), zinc (38.1% in Zinc1 and 38.6 in Zinc2) and silicon (0.57% in Zinc1 and 1, 03% in Zinc2). The presence of several materials (<1%) of phosphorus, sulfur, chlorine, potassium, calcium (only in Zinc2), titanium, chromium, manganese and nickel (only in Zinc2) was also found.

III. TESTS RESULTS

Initially the thicknesses of the samples were measured using a Mitutoyo micrometer, 0-25, 0.01mm, Nr. 103-137. For each sample, 4 measurements were made in each corner of the sample, considering the arithmetic mean as the thickness value.

E. DC pulses tests

For each type of sheet sample (Galvalume, IEE alloy, Aluminum, Zinc1 and Zinc2 (two different thicknesses of zinc sheet), applications with charge of 100 C, 150 C, and 200 C were performed.

Table I (see Annex) shows a summary with the values applied and measured. For these levels of charge and types of plates, perforations were verified in all samples.

The perforations were analyzed and the melt volumes were calculated according to (1).

All perforations have a rounded appearance and for each type of tile the perforate diameter generally increases with increasing charge.

F. Impulsive current tests

Table II (see Annex) shows a summary of current pulse applications with a standard waveform of 10/350µs. Some applications did not result in perforations.

In the case of calculation of perforated volume, the molten material was measured with a Mitutoyo electron microscope and was analyzed.

Except for the so-called aluminum sample, other samples did not perforate when peak current of 100 kA impulse were applied. At 150 kA, samples Zinc1 and Zinc2 did not perforate either and the sample called Galvalume had a small irregular hole. With 200 kA, all the samples presented perforations, as well as mechanical deformations in the plate. All aluminum samples showed perforations at all levels of impulsive current.

G. Statistical analysis of results

The standard [3] presents in Annex D the equation (1) that relates the volume of molten metal with the anode-cathode voltage drop and discharge current charge and also parameters of the material.

$$V = \frac{u_{a,c} \cdot Q}{\gamma} \cdot \frac{1}{C_W \cdot (\theta_S - \theta_U) + C_S} \qquad (1)$$

here

V is the volume of metal melted (m^3);

$u_{a,c}$ is the anode-or-cathode voltage drop (assumed as constant) (V);

Q is the charge of the lightning current (C);

γ is the material density (kg/m^3);

C_W is the thermal capacity (J/kgK);

θ_S is the melting temperature (°C);

θ_U is the ambient temperature (°C);

C_S is the latent heat of melting (J/kg).

It is known that aside from the charge and the volume all other expression terms are practically constant. We can thus isolate the volume-to-charge ratio, which can be determined through laboratory tests, starting from this premise.

Let's take the two sets of zinc (Zinc1 and Zinc2) plates with slightly different thicknesses to prove this premise by performing some statistical tests.

In the first group of plates designated Zinc1, the obtained results are shown in Table III and the ratio distribution of V/Q × Q, considering (1) of the points is showed in Figure 7:

TABLE III – TESTS ON PLATES Zinc1.

Charge [C]	Hole volume [mm³]	V/Q [mm³/C]
114.0	92.5	0.811
113.0	110.6	0.979
163.0	147.4	0.904
161.0	167.0	1.037
214.0	197.8	0.924
213.0	84.6	0.397
43.5	0.0	0.000
74.1	0.0	0.000
87.4	46.3	0.530

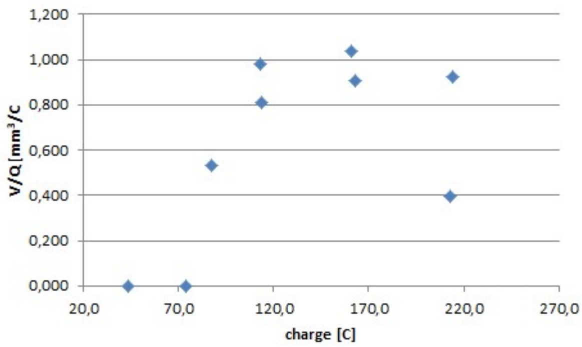

Figure 7 – Zinc1 tests.

We can note from the point cloud that the distribution seems to follow a certain pattern, that is, there must be some relation between them, which is opposite to the ideal that V/Q is constant. To study this statistically, and to count on something more structured than the mere observation of the points, we can use a linear regression. Starting with the correlation coefficient that relates numerical variables to each other, we estimate the degree of linear relationship between them.

The correlation coefficient R = 0.5705 and its corresponding coefficient of determination $R^2 = 0.3255$, are low and indicate that the accuracy of the regression equation must be smaller, that is the relation between them is a little weak, but the data are related.

The Durbin-Watson test [4-5] indicates that there may be an autocorrelation and so we should use a different model than the linear one. This becomes clearer when we place the line obtained from the regression next to the points. To illustrate, we can draw the line on the graph (Figure 8) by finding the regression equation as shown in (2).

$$V/Q=0.0039Q+0.1101 \qquad (2)$$

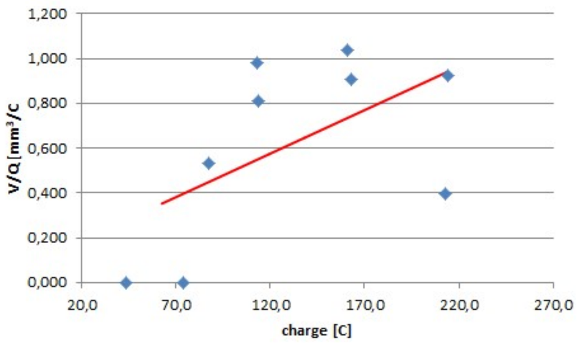

Figure 8 – Regression on the data of the plates Zinc1.

We realize that the line does not represent the points properly, but there may be some other function for that.

By analyzing the variance we can determine if the slope is zero, that is, we are dealing with a constant if the linear function adequately represents the points. In this case we confirm that the linear regression is not good for representing the points.

We have to start with the null hypothesis which defines that the V/Q relation follows a normal distribution with defined mean and standard deviation (slope is zero).

We used a significance level of 0.05 and we calculated the value of the test statistic as 3.3779.

The test statistic will follow a Fisher-distribution with first degree of freedom 1 and second degree of freedom 7 (number of data points minus 2), if the null hypothesis is valid.

With the level of significance equal to 0.05, first degree of freedom 1 and second degree of freedom 2, the critical value is 5.5914.

As our test statistical is less than the critical value, it can not reject the null hypothesis, i.e. the slope may be null or the straight line obtained is probably not useful.

In this case we define the constant V/Q by a mean value and a standard deviation to be (0.6204 ± 0.4093) mm^3/C. For a confidence level of 68% (1 standard deviation)

We have a second group of zinc samples, so-called Zinc2, which should have a similar behavior in the sieve of this analysis. The results are shown in Table IV.

The distribution of the data points is showed in Figure 9.

TABLE IV – TESTS ON PLATES Zinc2

Charge [C]	Hole volume [mm^3]	V/Q [mm^3/C]
113	95.0	0.8409
115	72.5	0.6301
162	139.4	0.8606
163	157.8	0.9682
215	219.9	1.0226
217	200.0	0.9215
47.9	0.0	0.0000
69.4	0.0	0.0000
91.6	13.7	0.1495

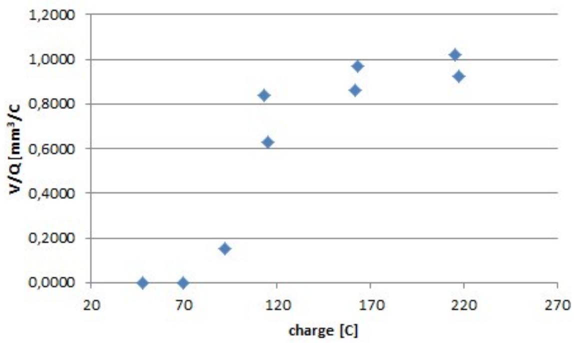

Figure 9 –Zinc2 tests.

We can note from the cloud of points that the distribution seems to follow a certain pattern, that is, there must be some relation between them, which is against the ideal that V/Q is constant. Even this pattern resembles that of the distribution of the Zinc1 plate.

The correlation coefficient $R = 0.8823$ and its corresponding coefficient of determination $R^2 = 0.7785$, are high and indicate that the accuracy of the regression equation must be reasonable, i.e. the ratio between them is a reasonably strong one and the data are related issues.

The Durbin-Watson test [4-5] indicates that there may be an autocorrelation and so we should use a different model than the linear one. This becomes clearer when we place the line obtained from the regression next to the points.

To illustrate, we can draw the line on the graph (Figure 9) by finding the regression equation (3).

$$V/Q=0,0062Q-0,2298 \qquad (3)$$

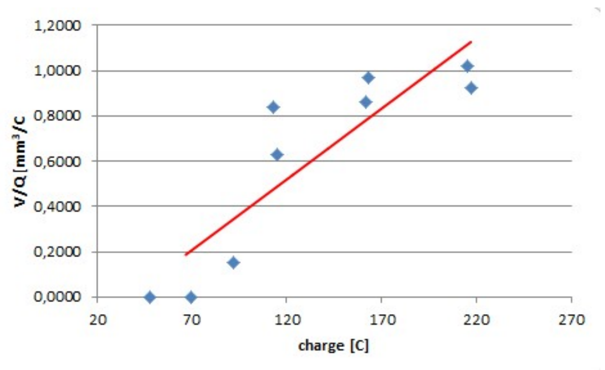

Figure 9 – Regression on the data of the plates Zinc2.

Apparently, the distribution of the points is similar to that of the Zinc1 plate, however the numbers contradict this statement. Even the way the line is placed in relation to the points seems to indicate that it fits better in this case, but it is still apparent that another regression would be better to describe the points.

By analyzing the variance we can determine if the slope is zero, that is, we are dealing with a constant. Thus, the null hypothesis is that the V / Q relation follows a normal distribution with defined mean and standard deviation (slope is zero).

We used a significance level of 0.05, we calculated the value of the test statistic as 21.6022.

The test statistic will follow a Fisher-distribution with first degree of freedom 1 and second degree of freedom 7 (number of data points minus 2) if the null hypothesis is valid.

With the level of significance equal to 0.05, first degree of freedom 1 and second degree of freedom 2, the critical value is 5.5914.

As our test statistic is greater than the critical value, we can reject the null hypothesis, that is, the slope is not null.

This result is different than expected, indicating that plates Zinc1 and Zinc2 behaved differently in V/Q. This is confirmed by the different regression equations for the two cases, although the distribution of the points still suggests similarity between them. This suggests that further testing with more samples is needed to more accurately define these relationships and may indicate a minimum threshold for which the standard expression is valid. Below this limit there is no hole, so there is no measurable V/Q relation. We can also propose in a future study to use bar-shaped electrodes in order to standardize the consumption of material, which would increase the accuracy of the evaluation of loss of mass and volume with objects more easily defined. This configuration would also aid in the evaluation of the behavior of the sensors against atmospheric discharges.

For the purpose of comparison with sheet Zinc1, we define the constant V/Q for sheet Zinc2 by a mean value and a standard deviation as (0.5993 ± 0.4283) mm^3/C. For a confidence level of 68% (1 standard deviation). This is a very similar value to that of sheet Zinc1 (0.6204 ± 0.4093) mm^3/C.

Let us assume that the relation V/Q is constant for the purpose of this work.

In this case we can calculate the average of all points including sheet Zinc1 and Zinc2 to obtain a Zinc average value and a standard deviation as (0.6098 ± 0.4065) mm^3/C. For a confidence level of 68% (1 standard deviation) and therefore this is the value for zinc sheets.

We can apply the same concept to other material plate, for example aluminum. Thus, in this case we will have:

In the first group of plates named Al the following results were obtained.

TABLE V – TESTS ON ALUMINUM PLATES

Charge [C]	Hole volume [mm^3]	V/Q [mm^3/C]
107	302.2	2.8241
108	302.2	2.7980
153	454.7	2.9719
157	373.1	2.3762
202	458.0	2.2673
202	438.4	2.1702
47.8	333.8	6.9840
65.01	296.9	4.5668
92.01	458.3	4.9813

The distribution of the points follows the behavior as shown in Figure 10.

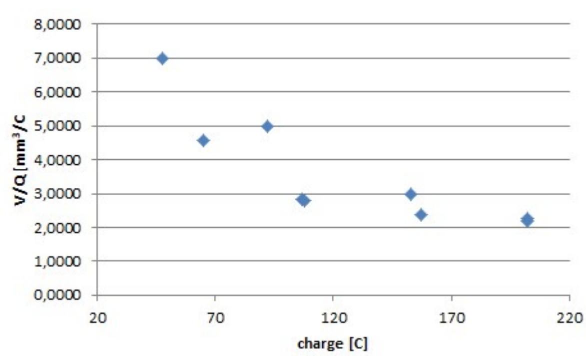

Figure 10 –Aluminum tests.

We can note by the point cloud a very specific distribution forming a very specific pattern, inversely proportional and very close to a line. To prove statistically we can use a linear regression. Starting with the correlation coefficient that relates numerical variables to each other, we estimate the degree of linear relationship between them.

The correlation coefficient $R = 0.8335$ and its corresponding coefficient of determination $R^2 = 0.6948$, are very high and indicate that the accuracy of the regression equation is reasonable. In the informal table, it is classified as a reasonably strong relationship, indicating that the data are related.

To illustrate, we can draw the line on the graph by finding the regression linear equation as shown in (4).

$$V/Q=-0{,}0243Q+6{,}6139 \quad (4)$$

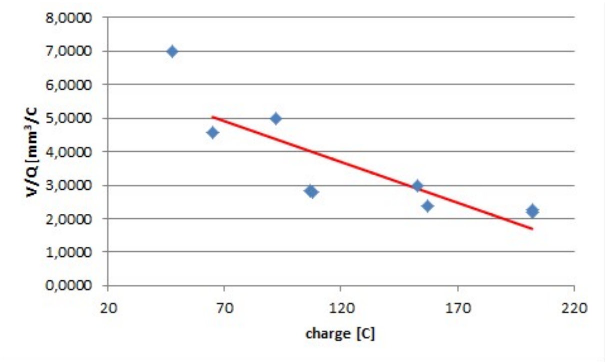

Figure 11 – Regression on the data of the aluminum plates.

By analyzing the variance we can determine if the slope is zero, that is, we are dealing with a constant. Thus, the null hypothesis is that the V/Q relation follows a normal distribution with defined mean and standard deviation (slope is zero).

We used a significance level of 0.05, we calculated the value of the test statistic as 15.9342.

The test statistic will follow an F distribution with first degree of freedom 1 and second degree of freedom 7 (number of data minus 2) if the null hypothesis is valid.

With the level of significance equal to 0.05, first degree of freedom 1 and second degree of freedom 2, the critical value is 5.5914.

As our test statistic is greater than the critical value, it can reject the null hypothesis, i.e., the slope is not null.

Leaving aside these considerations in order to advance the argument, we consider, as before, that the value of the ratio V/Q is constant with a value of (3.5489 ± 1.6290) mm³/C for aluminum, without prejudice to the evaluations of this work.

We call the relationship V/Q as the volumetric melting constant of the material as a function of the charge KFQ as shown in (5).

$$K_{FQ} = V/Q \quad (5)$$

From the numbers obtained in the tests we will have that for the zinc the value of the constant is:

$K_{FQZn} = (0.6098 \pm 0.4065)\ mm^3/C$

For aluminum it is:

$K_{FQAl} = (3.5489 \pm 1.6290)\ mm^3/C$

From the premise that these constants are valid for an approximate evaluation we can establish equivalence relations for different metallic materials used in roofing.

Initially we must consider that the area covered is constant independent of the material used, and we can only vary the volume by the thickness of the sheet used in the cover.

Considering two materials with different constants K_{FQ1} and KFQ2 submitted to the same charge Q we can establish equality:

$Q = V_1 / K_{FQ1} = V_2 / K_{FQ2}$

Assuming the constant area for the plates the equality establishes a relation between the thicknesses and the constants:

$e_1 / e_2 = K_{FQ1} / K_{FQ2}$

Thus, supposing that material 1 is aluminum and material 2 is zinc we will have a relation:

$e_{Al} / e\ e_{Zn} = 3.5489 / 0.6098 = 5.8$

That is, when replacing a zinc tile with an aluminum tile the thickness of the latter would have to be approximately 5.8 times greater to obtain the same effect with regard to the possibility of perforation by discharge.

Considering the normalized parameters for minimum thickness in Table VI copied from standard [1].

There are several gaps in this table, but considering the above, if the standard admits a thickness of 7mm for aluminum, then we deduce that for zinc this minimum thickness would be 1.21 mm so that drilling (hot spots etc.) does not occur.

It is assumed that the minimum thickness, considering the electrical and thermal aspects of conduction or fusion of metallic material by the current of the atmospheric discharge, in cases where it is not important to prevent drilling, hot spots or problems with ignition is limited by the capacity current (fusible link effect) and therefore the thickness values are very similar.

As a function of this, if we consider that the copper constant KCu is 10.244 and compared with other matrices as in Table VII, we can obtain some relations:

TABLE VII – RELATIONSHIP BETWEEN MATERIALS

Material	K_{mat}	K_{Cu} / K_{mat}	e_{mat}/e_{Cu}
Aluminum	7.585	1.35	1.22
Iron	3.148	3.25	2.20
Tin	1.642	6.24	3.39

Based on this information (considering only the electrical and thermal effects of the lightning current) for the normalized thickness of copper 0.5 mm corresponds a thickness of approximately 0.61 mm of aluminum, 1.1 mm of iron and 1.7 mm of tin. We do not have exact values for normalized materials, but we can see that probably the minimum section when there is no problem with drilling is limited by a possible fuse effect when conducting the atmospheric discharge current. Thus, the equivalence study should be aimed at finding equivalence between the fuses of various materials, which for that application would be those used in covers.

This sets some directions for other experiments, which basically divide into two cases:

- study of arc between electrodes formed by bars of metallic material in order to determine the wear of material by the arc;
- study of fusion of materials by the passage of electric current. Although this topic has been studied for a long time the research on the specific materials of metal roofs is not, as they are not necessarily applicable as fusible links.

Another reason for the definition of the minimum thickness of sheet metal would be the mechanical question which has no relation to the effects of lightning on metal tiles, but to the mechanical stresses on the surfaces of the sheets or fixings due to excessive weights in shingles or stresses due to wind or rain.

IV. FUTURE WORKS AND CONCLUSIONS

In this work, the compositions of samples of metallic tiles used in roofs of structures were analyzed. The results of current tests simulating continuing currents and impulsive currents in these tiles were also analyzed.

Considering the small number of tests performed, a statistical analysis was performed to analyze the results of the tests.

Further investigations will be carried out in future work to verify the carrying capacity of lightning currents and the effects of these currents on connections (for example, between small sensor rods and shingles) and splicing on metal shingles.

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ANNEX

TABLE I – TESTS WITH CONTINUOUS CURRENT PULSES

SAMPLE #	TYPE	THICKNESS (mm)	CURRENT (A)	DURAÇÃO (ms)	CHARGE (C)	AVERAGE HOLE DIAMETER (mm)	Area (mm^2)	Volume (mm^3)	V/Q (mm^3/C)
6	GALVALUME	0,449	442,1	232	103	13,1	134,8	60,5	0,588
6	GALVALUME	0,449	442,9	228	101	16,5	213,8	96,0	0,951
17	LIGA IEE	0,385	447	233	104	19	283,5	109,2	1,050
17	LIGA IEE	0,385	449,2	229	103	17,5	240,5	92,6	0,899
21	ALUMÍNIO	0,7625	427,1	251	107	22,5	397,6	303,2	2,833
21	ALUMÍNIO	0,7625	429,6	252	108	22,5	397,6	303,2	2,807
29	ZINCO 1	0,456	439,7	259	114	16	201,1	91,7	0,804
29	ZINCO 1	0,456	434,7	259	113	17,5	240,5	109,7	0,971
38	ZINCO 2	0,594	443,1	256	113	14,2	158,4	94,1	0,832
38	ZINCO 2	0,594	447,2	257	115	12,4	120,8	71,7	0,624
7	GALVALUME	0,442	447,2	319	143	19,1	286,5	126,6	0,886
7	GALVALUME	0,442	442,3	321	142	21,5	363,1	160,5	1,130
18	LIGA IEE	0,355	437,5	318	139	21,4	359,7	127,7	0,919
18	LIGA IEE	0,355	440,4	320	141	23	415,5	147,5	1,046
22	ALUMÍNIO	0,76	416,7	367	153	27,6	598,3	454,7	2,972
22	ALUMÍNIO	0,76	423,6	370	157	25	490,9	373,1	2,376
30	ZINCO 1	0,455	441,6	369	163	20,2	320,5	145,8	0,895
30	ZINCO 1	0,455	435,5	369	161	21,5	363,1	165,2	1,026
39	ZINCO 2	0,595	437,9	370	162	17,2	232,4	138,2	0,853
39	ZINCO 2	0,595	441,6	369	163	18,3	263,0	156,5	0,960
8	GALVALUME	0,469	443,1	487	216	25,5	510,7	239,5	1,109
8	GALVALUME	0,469	441,1	484	214	25,6	514,7	241,4	1,128
19	LIGA IEE	0,383	437,3	484	212	26,1	535,0	204,9	0,967
19	LIGA IEE	0,383	443,2	484	215	26	530,9	203,3	0,946
23	ALUMÍNIO	0,761	415,6	487	202	27,7	602,6	458,6	2,270
23	ALUMÍNIO	0,761	414,9	488	202	27,1	576,8	438,9	2,173
31	ZINCO 1	0,447	438,5	488	214	23,4	430,1	192,2	0,898
31	ZINCO 1	0,447	435,8	448	213	15,3	183,9	82,2	0,386
40	ZINCO 2	0,59	441,5	487	215	21,6	366,4	216,2	1,006
40	ZINCO 2	0,59	442,8	490	217	20,6	333,3	196,6	0,906

TABLE II – TESTING WITH CURRENT IMPULSES

SAMPLE #	TYPE	THICKNESS (mm)	CURRENT (kA)	WAVEFORM (µs)	CHARGE (C)	W/R (kJ)	AVERAGE HOLE DIAMETER (mm)	Area (mm^2)	Volume (mm^3)	V/Q (mm^3/C)
1	GALVALUME	0,482	106,7	13,1/376	44,6	2593	WITHOUT HOLE	---	---	0
11	LIGA IEE	0,41	102,2	13,4/389	47,8	2698	WITHOUT HOLE	---	---	0
3	GALVALUME	0,47	154,2	12,9/401	74	6029		14,208	6,678	0,09024
13	LIGA IEE	0,427	152,6	13,7/420	80,3	6492	9,018	63,872	27,273	0,339643
26	ALUMÍNIO	0,766	98,5		47,8	2117	23,649	439,272	336,483	7,039384
27	ALUMÍNIO	0,761	159,4		65,01	5649	22,302	390,658	297,291	4,573003
28	ALUMÍNIO	0,755	202,8		92,01	9599	27,71	603,096	455,337	4,948782
35	ZINCO 1	0,455	106,1		43,5	2313	WITHOUT HOLE	---	---	0
36	ZINCO 1	0,458	156,3		74,1	6465	WITHOUT HOLE	---	---	0
37	ZINCO 1	0,456	205,7		87,4	9146		100,669	45,905	0,525232
43	ZINCO 2	0,598	102,4		47,9	2459	WITHOUT HOLE	---	---	0
44	ZINCO 2	0,606	148,9		69,4	5839	WITHOUT HOLE	---	---	0
46	ZINCO 2	0,595	207,2		91,6	9815		22,811	13,573	0,148173

* - Irregular small hole
** - Rip on the side of the mark

TABLE VI – Minimum thickness of metal sheets or metal pipes in air-termination systems [1]

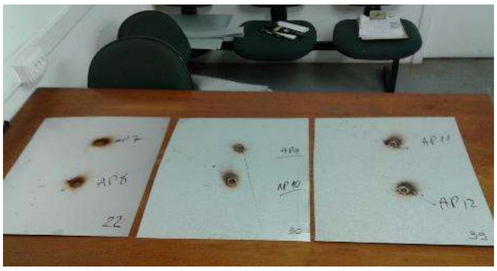
Class of LPS	Material	Thickness[a] *t* mm	Thickness[b] *t2* mm
I to IV	Lead	–	2.0
	Steel (stainless, galvanized)	4	0.5
	Titanium	4	0.5
	Copper	5	0.5
	Aluminum	7	0.65
	Zinc	–	0.7

[a] *t* prevents puncture.
[b] *t'* only for metal sheets if it is not important to prevent puncture, hot spot or ignition problems.

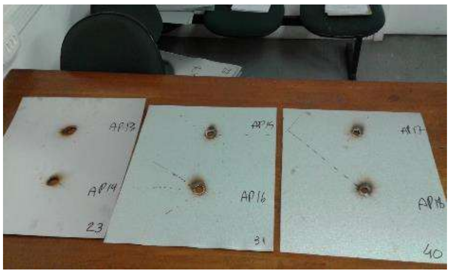
SOME PHOTOS OBTAINED IN TESTS:

Continuing tests - Galvalume and IEE

AL, Zinc1 and Zinc2 – 100 C

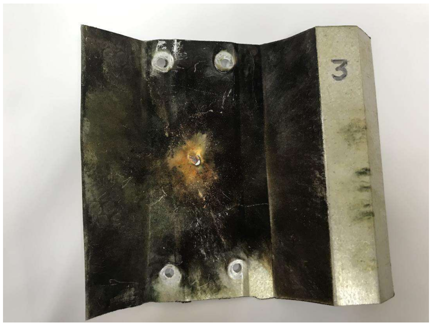


AL, Zinc1 and Zinc2 – 150 C



AL, Zinc1 and Zinc2 – 200 C

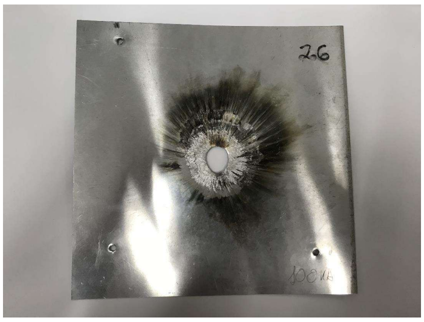
Impulsive tests: Galvalume 100 kA



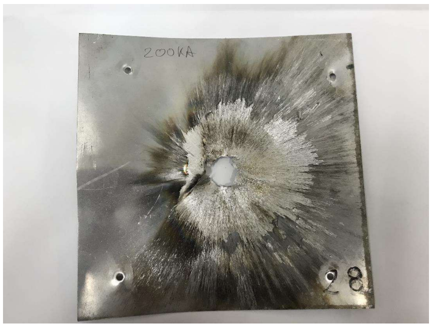
Galvalume 150 kA

IEE 100 kA

IEE 150 kA



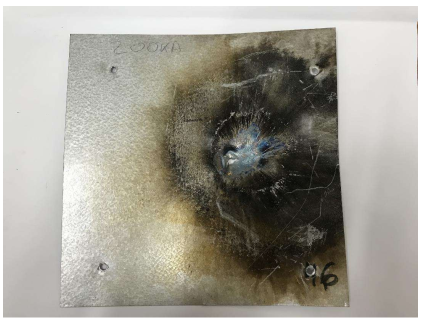
Al 100 kA



Al 200 kA

Zinc1 – 150 kA

Zn 2 – 150 kA



Zn 2 – 200 kA