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THE INFLUENCE OF THE AXIAL TENSION ON THE LINEAR RESISTANCE AND MECHANICAL PROPERTIES OF AlMgSi ALLOY OVERHEAD LINE CONDUCTORS

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The paper examines the influence of axial tension on the linear electrical resistance of single-layer aluminum alloy conductors and showed that when the tension is applied the linear resistance stabilizes at a lower level in comparison to conductors with no tension or with low value of tension. The effect of pressure forces occurring in the inter-wire contact area was also examined and it was found that the hardness of the material and the range of deformation locally increases as the average pressure at maximum compression force increases.

Keywords: AlMgSi alloy, conductor, electrical tension, resistance, hardness

INTRODUCTION

Each phase conductor in the span of an overhead line (OHL) is subjected to axial tension. Its value varies in time in terms of e.g. temperature and the icing weight and therefore determining the conductor's sag. The range of allowable tension is limited by the relevant standards and in typical operating conditions it is between 10 % and 40 % of the conductor's rated strength. Due to the axial tension applied to the OHL conductor significant pressure forces occur at the contact areas of individual wires. In the case of a single-layer conductor these forces occur only at the areas of linear contact between the outer layer wires and the central wire as gaps between the outer layer wires are used for technological and operational reasons. The authors in [1 – 3] have created mathematical models which allow calculating of the values of the inter-wire pressure force as a function of axial tension as well as technical-constructional parameters, material characteristics and experimental research data. These pressure forces create significant local deformations of the individual wires at the contact area, thus, according to general knowledge, affecting the value of the electrical contact resistance in the area of inter-wire contact [4]. The nominal linear resistance of the conductor is calculated as a parallel connection of resistors out of which each represents the electrical resistance of a particular wire in the OHL conductor. Therefore, the lower the lay length (the distance required to complete one revolution of the strand around the diameter of the conductor) the higher the electrical resistance of a single-layer cable assuming that each wire of the strand is identical [5]. One must take into account that the OHL conductor while operating is subjected to permanent axial tension which should lower the electrical contact resistance of the OHL conductor as a whole [6]. Experimental verification of this assumption allows for an additional factor to be taken into account – the influence of the axial tension on the electrical resistance of the OHL conductor in terms of current-carrying capacity and energy transmission losses.

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EXPERIMENTAL PROCEDURE

During the research on the influence of the axial tension on the linear electrical resistance a single-layer mono-material OHL conductor with a typical 1 + 6 x 2,54 mm structure composed of round wires made of aluminum alloy with parameters as presented in Table 1 was used (35-AL3 according to EN 50182, name: CEDAR).

Table 1 **Physical and mechanical properties of used overhead line conductor according to standards [7, 8]**

Parameter	Value
Wire's diameter / mm	2,54
OHL conductor's outer diameter / mm	7,62
OHL conductor's cross-sectional area / mm^2	35
Lay length of the outer layer / mm	76,2-106,7
Rated strength of the conductor / kN	10,5
Coefficient of linear expansion / °C^{-1}	23x10^{-6}
Modulus of elasticity / GPa	63,3
DC resistance at 20 °C / Ω/km	0,927
Mass per unit length / kg/km	96,8

Table 2 **Chemical composition of the ingots used during compression tests / wt. %**

Al	Mg	Si	Fe	Mn	Zn	Other
97	0,97	1,07	0,22	0,46	0,2	0,802

Electrical resistance measurements

Electrical resistance tests were conducted on a Thomson bridge (Resistomat 2304, Burster with measurement accuracy ≤ 0,01 %) inside of an air-conditioned laboratory at 20 °C with a gauge length of 1 000mm. The conductor was installed on a testing machine dedicated for OHL conductors testing (Brydex, with force measurement accuracy ≤ 0,5 %) and the initial axial tension of 100 N was applied. Then a threefold axial tension loading cycle of 5 %, 10 %, 20 %, 30 % and 40 % of the conductor's breaking load (Table 1) was applied with unloading to the initial value of 100 N between each increase in the axial tension. The tests were carried out for 4 OHL conductor samples and average values of the measured electrical resistance was calculated.

Compression test

Qualitative assessment of the influence of deformation resulting from various variants of inter-wire contact in OHL conductors on mechanical properties was conducted during simulation in static compression test of the rods with 40 mm in diameter which were cut in half along the axis and arranged as in Figure 1. The maximum force of approx. 6 kN/mm was applied with the use of a testing machine which force and displacement measurements accuracy equals 1 %. In theory this experiment (when in the right scale) allows to assess the effects of the linear contact force on the inter-wire contact area.

The chemical composition of the rods used during simulation is presented in Table 2. These rods were chosen for this research as its initial hardness corresponds with the mechanical properties of the wires in the OHL conductor (UTS 308 MPa, YS 283 MPa). In order to calculate that the relation proposed by Tabor [9, 10] which combines hardness with yield stress of the material was used.

After a static compression test of half-cylinders in linear contact conditions was conducted the contact width was measured (which made it possible to estimate the values of the average pressure which is a quotient of the maximum force and contact area of the half-cylinders). Afterwards, each sample was cut in half, and subjected to Vickers hardness test in the radial normal direction to contact surface.

Vickers hardness test

The rods' hardness both in the initial temper and after the compression test was measured using Vickers method (HV5) on Tukon 2500 hardness tester (at 50 N load with indentation time of 10 seconds and measurement accuracy of 1 %). As presented in Figure 1, each sample was subjected to 9 indentations made in the sample axis at 2 mm intervals. The average values of 9 indentations were calculated from 4 samples of each deformation variant.

RESULTS AND DISCUSSION

Electrical resistance study

The impact of the axial tension on the linear electrical resistance of the OHL conductor is presented in Figure 2. The applied axial tension results in changes in linear electrical resistance – the greater the tension the lower the electrical resistance of the OHL conductor. The discussed influence of the axial tension is significant from the technical point of view as it results in a decrease of a linear electrical resistance of the OHL conductor by up to approx. 3 %. Such changes in electrical resistance cannot be associated solely with the axial and radial elastic deformation of the conductor wires. It is postulated that the decisive factor for the decrease in the linear electrical resistance of the conductor due to the axial tension is the decrease in inter-wire contact electrical resistance. The relation between the value of the axial tension and the measured electrical resistance is non-linear.

The largest changes occur when relatively low axial tension of 5 % - 10 % is applied. Further increase of the axial tension results in only a slight decrease of the linear electrical resistance. A probable cause of the significant changes in electrical resistance at low values of axial tension is the phenomenon of springing-back of the outer

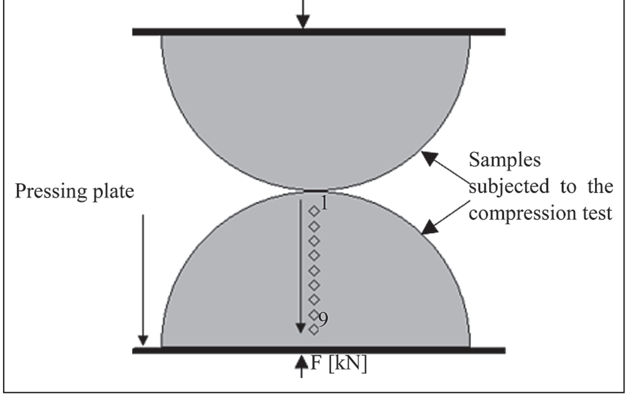

Figure 1 Compression test of the aluminum alloy samples with the marked places of the later indentations (1 – 9) which were made during Vickers hardness test

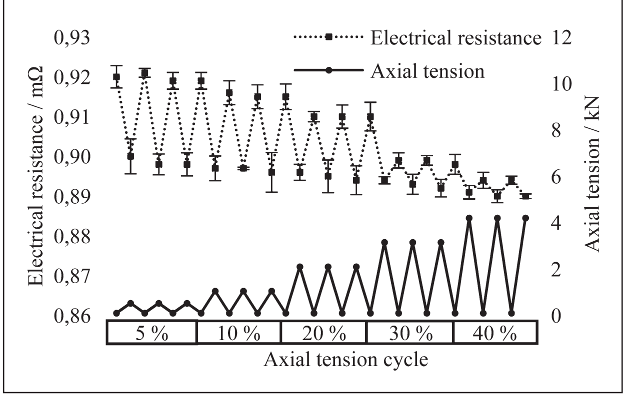

Figure 2 The influence of the axial tension on the electrical resistance OHL conductor with standard deviation marked as error bars

layer wires from the central wire (residual stresses formed in the wires after the wire stranding operation). This phenomenon makes difficult to maintain the contact between the central wire and the outer layer wires. It is also worth noting that in terms of the 5 % cycle when the axial tension is removed the linear electrical resistance of the OHL conductor returns close to the initial value which is not the case with higher tension. The greater the axial tension the smaller the difference between the linear electrical resistance measured under the axial tension and after it is removed to initial 100 N. It implies that local plastic deformations of the wires in the inter-wire contact areas occur. An indirect confirmation of this hypothesis is the fact that subsequent axial tension cycles up to the identical value no longer significantly affect the value of the linear electrical resistance of the OHL conductor. Such observation correlates with the general knowledge on the changes in the contact electrical resistance of wires in various configurations of position where removing the contact area tension does not result in an analogous increase of the electrical resistance as oppose to its decrease when the tension is applied [4].

The observed decrease of the linear electrical resistance of the OHL conductor as a result of the axial tension may have a practical effect and it might be reasonable to pre-load the OHL conductors with high axial tension for a short period of time during installation with so-called overstraining which is often used in order to reduce the creep effect of the conductors. It would lower the linear electrical resistance of the conductors and reducing it by approx. 3 % might compensate for the energy transmission losses while maintaining the identical current intensity (transmission losses are proportional to the product of the square of the current value and conductor's electrical resistance). However, confirmation of the beneficial practical effect requires further research, e.g. to what extent the observed decrease in electrical resistance is permanent. It should be remembered that aluminum and its alloys tend to form a tight oxide layer due to the exposure to atmospheric conditions, which may increase the inter-wire contact electrical resistance, thus resulting in the increase of the linear electrical resistance of the OHL conductor.

Compression test analysis

Calculations based on the theoretical models prove that pressure forces caused by axial tension generate state of stress in the wires which leads to local plastic deformation of the material (around their mutual contact area) even at relatively low values of the axial tension. In order to represent this phenomenon model simulation was conducted, i.e. static compression test of half-cylinders in the linear conditions which allowed the estimation of the range of the plastic deformation zone. Figure 3 presents collective graph of the linear pressure force as a function of displacement for each of the examined cases.

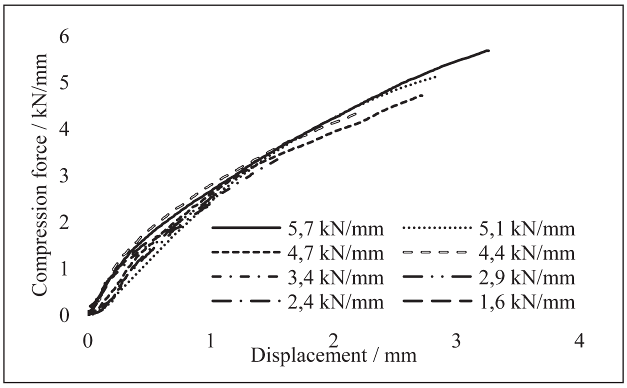

Figure 3 Compression force in the function of displacement with the maximum force of 50 kN (5,7 kN/mm)

Figure 3 clearly shows the general quasilinear nature of the linear pressure force versus displacement which may be associated with the total compression of half-cylinder radius. When considering lower values of pressure force and the correlating displacement values the angle of inclination is significantly higher. Taking into account data in Table 3 the quasilinear relation between linear pressure force and the final inter-wire contact width is also evident as well as the correlation between the linear pressure force and the average pressure at maximum compression force at the tested range of forces.

Vickers hardness test

The results of the Vickers hardness test of the samples subjected to the compression test as well as the initial samples are summarized in Table 3. The gray gradient was used in order to easily illustrate the change in hardness from the 1st measuring point which was at the potentially the most deformed place of each sample to the 9th measuring point which was closest to the center of the half-cylinder, and thus in the potentially least deformed place. The average hardness value of the initial

Table 3 **Average hardness values of all the samples along with the reference sample. The darker the shade of the cell the higher the value of the samples subjected to the compression test.**

Indentation order	Maximum compression force / kN/mm								
	0	1,6	2,4	2,9	3,4	4,4	4,7	5,1	5,7
	Final contact width / mm								
	0	5,8	8	9,1	9,5	12	12,8	13	13,7
	Average pressure at maximum compression force / MPa								
	0	277	297	320	353	363	368	395	415
	Hardness / HV5								
1	105	114	116	118	129	130	132	133	133
2	106	115	116	114	125	125	124	130	131
3	106	112	116	117	122	122	119	128	126
4	108	108	115	117	116	118	119	124	125
5	109	104	112	115	115	116	118	122	125
6	108	106	105	108	114	117	117	122	125
7	105	104	103	106	115	117	115	119	126
8	103	105	105	107	111	116	120	120	122
9	105	103	103	105	111	118	116	119	123

non-deformed half-cylinder is 106 HV5. A local increase in the material hardness was observed as the higher the pressure force the higher the hardness values with the maximum of 133 HV5. Considering the lowest applied linear pressure force (1,6 kN/mm) the range of the hardness changes reaches approx. 30 % of the final thickness of the half-cylinder. Subsequent investigated cases (linear pressure force of 2,5 kN/mm and 2,9 kN/mm) generated hardness changes in about half of the thickness of the half-cylinders, whereas higher values of the pressure force resulted in a material hardness change in the entire sample. The range of the observed changes in hardness values might be an approximate measure of the range of the occurring plastic deformation of the material caused by the linear pressure force and the values might be an indirect measure of the size of this deformation.

CONCLUSIONS

Taking into consideration the conducted research on the 35-AL3 OHL conductor and AlMgSi rods the following conclusions may be drawn:

The axial tension applied to the OHL conductor results in the decrease of the linear electrical resistance. Considering the typical axial tension of the conductors (10 % - 40 % of the rated breaking strength) the values of the conductor's linear electrical resistance are lower by approx. 3 % than with no axial tension. The probable causes of the observed decrease in linear electrical resistance of the OHL conductor are phenomena related to the decrease in contact electrical resistance in the area of inter-wire contacts due to the occurring linear pressure forces.

The positive effect of the axial tension occurring during the operating of the OHL conductor on its electrical resistance does not disappear when the tension is decreased. The final electrical resistance is determined by the first tension cycle. The difference between the electrical resistance of the OHL conductor with the applied axial tension and after its release is lower when the value of the tension was higher.

The observed decrease in the electrical resistance of the OHL conductor is a favorable phenomenon from an operational point of view (lower Joule heating; lower transmission losses).

A quasilinear relation between the linear pressure force and both the deformation of wires and the final inter-wire contact width occurs.

The pressure forces may generate plastic deformations at the inter-wire contact areas. The range of the plastic deformation and its value increase along with the increase of the linear pressure force.

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