Hungarian Materials and Chemical Sciences and Engineering, Volume 47, No. 1 (2023), pp. 53–62.
http://doi.org/10.32974/mse.2022.005

ELASTICITY AND HEAT RESISTIVITY OF HEAT-TREATED HIGH VOLTAGE CONDUCTORS

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Abstract: The increase in electricity demand puts a large load on electricity transmission and distribution networks. A quick solution for a given section is to replace the conductor with high-temperature low sag conductors. A continuous operating temperature of 150–200 °C instead of 80 °C means a higher current carrying capacity. However, an important issue is the size of the clearance, that is, the sag of the conductor. It is necessary to consider the change in the sag not only at the operating temperature but also in case of possible overloading. The value of the sag may be different from one span length to another, so it is worth examining the elastic behavior of the conductors in a general study. The article presents the results of this study for three conductors constructed from different aluminum alloys and steel grades. Standard ACSR conductor tested which contain hard drawn, unalloyed aluminum wires and galvanized steel wires. An AACSR conductor is produced with the same construction as ACSR one from alloyed aluminum wires and galvanized high strength steel wire which was also tested. The results compared to the measured values of a high-temperature low sag conductor consisting of heat-resistant aluminum wires and aluminum cladded steel wires.

Keywords: Aluminum, High voltage, Conductor, HTLS, Heat resistivity

INTRODUCTION

Nowadays, high-temperature low sag (HTLS) conductors are gaining an increasingly wide range of applications [1, 2]. In electric energy transport, the maximum operating temperature for classic ACSR, AAC, and AAAC lines is limited to 80 °C [3]. This is due to the fact that in the planned durable operation, the annealing of the hard-drawn unalloyed aluminum wires above 100 °C will surely begin. The lower strength of the conductor has a larger sag, in this case, the clearance is not trusted [4]. In the event of a sudden increase in energy demand, the quickest solution is to replace the conductor with another that provides a higher current-carrying capacity at higher operating temperatures [5]. The limit of this is, of course, the maximum permissible mechanical load of the existing towers. It dictates the conductor with the highest cross-section and mass that can be applied for this task [6]. However, a significant increase in current carrying can still be achieved [7].

There are two basic types of HTLS conductors [2]. In one case, the conductors are made of heat-resistant aluminum alloy and their construction corresponds to the structure of classic

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ACSR wires. In the other type, soft unalloyed aluminum wires (AL0) are held by a high-strength core [3]. For soft aluminum wires, heat resistance is not an issue, the heat resistance of the reinforcing core determines the maximum operating temperature. In case of a heat-resistant aluminum alloy, cold-drawn wires are used to ensure the strength of the conductor. Here, heat resistance is determined by the onset of recrystallization, and its temperature [8]. It is necessary to give the temperature at which recrystallization begins in the wire. Here it is necessary to consider that the planned period of operation is at least 40 years.

The study of the performance of complex structures is an ongoing issue not only for conductors [9]. The electrical resistance and current carrying capacity are determined by the material, state, and diameter of the wires, and the structure of the conductor. The article examines and compares wires of a similar structure, consisting of hard-drawn wires. This way, it is possible to focus on the differences given by the alloy.

Considering the mechanical behavior of wires, it is not the tensile strength but the elastic properties that are important for operation [10]. The elastic properties of the stranded conductors are described by the stress-strain characteristic. The stranded structures are not linearly elastic, and their creep is also an important issue in terms of clearance, i.e. the sag value [11, 12]. Of course, short-term creep is also an issue of the regulation of a line. These phenomena are involved in the standard stress-strain test described by the EN 50182:2001 standard. These tests evaluate the conductors. Therefore, the transmission system operators require these tests from the producers through a complete type test report. The actual construction and the wire properties has a strong influence on the stress-strain characteristic therefore it is just reported by the producers to the users due to the production specific issues. The transmission line planning CAD applications are using producer specific databases.

The measurement of the stress-strain characteristic manages the conductor structure in one. This is important because it is not only the phase transformation of aluminum wires that causes a change in high temperature but also the reinforcing steel strand. Thus, it is important to study the phase transformation of not only aluminum but also steel materials using modern methods [13].

An increasingly common method is the surface treatment of conductors due to the reduction of corona radiation [14]. Corona radiation can cause serious loss and noise exposure, so it is essential to reduce its degree [15]. Several methods are being developed for this, such as blasting, thin films, or the use of special oxide layers [16, 17, 18]. Currently, the blasted surface is used in production, the others are in the experimental phases. However, their common feature is that they also change the emission of the surface [19]. This changes the thermal balance of the conductors, which causes a change in the current carrying capacity [20]. For this reason, it is worth comparing conductors of different materials with the same surface quality.

The article presents the change in the elastic properties of conductors manufactured from wire grades Al1, Al4 and AT1 after operation at elevated temperatures and high temperatures. The operating conditions were simulated in a laboratory with a high current load, where the applied current heated the conductors. In each wire, the reinforcements were strands made of steel wires of different strengths (ST1A, ST6C, and A20SA). Thus, typical types of conductors could be compared during the tests. Based on the stress-strain characteristics of the conductors, the elastic behavior of the conductors was determined, which is a common method in the design practice.

1. MATERIALS AND METHODS

1.1. Tested conductors

Three different types of conductors were tested: I. ACSR 264-AL1/34-ST1A, II. AACSR 185-AL4/43-ST6C, III. AACSR 264-AT1/34-A20SA. The construction, material, and properties of the conductors are shown in *Table 1*. AL1 means hard drawn unalloyed aluminum wires, which are made from generally EN AW 1370 alloy. AL4 wires are from alloyed grade, generally from EN AW 6101, which contains 0.5 w/w% magnesium. The wires are stabilized at 175 °C, 4-5 hours after the wire drawing process. AT1 designation shows the heat-resistant alloy, which contains zirconium in its alloy. ST1A is the name of the normal heavily galvanized high-carbon steel wire. ST6C means steel wires with much higher strength, but smaller zinc on the surface of the wire. The strength and the zinc content are determined by the diameter of the wires. A20SA is the designation of the aluminum cladded steel wire. The zinc layer of normal galvanized wires oxidized rapidly in elevated temperatures. Therefore, this type of steel wire is applied in HTLS conductors. The cladding process is generally made by aluminum extrusion at higher temperatures than the galvanization process. Therefore, the strength of this type of wire is smaller than the other sintroduced ones.

Table 1
The construction and properties of the tested conductors according EN 50182

Conductor	I.	II.	III.
Industrial name	264-AL1/34-ST1A case 0	185-AL4/43-ST6C case 0	264-AT1/34-A20SA case 0
Standard	EN 60889 / EN 50189	EN 50183 / EN 50189	EN 50182 / EN 61232
Construction	ST1A (1 + 6) × 2.49 mm	ST6C (1 + 6) × 2.8 mm	A20SA (1 + 6) × 2.49 mm
	AL1 (+9 + 15) × 3.74 mm	AL4 (+12 + 18) × 2.8 mm	AT1 (+9 + 15) × 3.74 mm
Conductor diameter	22.4 mm	19.6 mm	21.85 mm
Calculated cross-section area	ST1A 34.1 mm^2	ST6C 43.1 mm^2	A20SA 34.07 mm^2
	AL1 263.7 mm^2	AL4 184.7 mm^2	AT1 263.7 mm^2
	Overall 297.7 mm^2	Overall 227.8 mm^2	Overall 297.7 mm^2
Linear mass of the conductor	994.4 kg/km	847.1 kg/km	960.61 kg/km
Rated tensile strength	81.04 kN	120.81 kN	83.62 kN
Resistance of the conductor	Max. 0.1095 Ω/km	Max. 0.1805 Ω/km	Max. 0.1113 Ω/km

The elastic moduli of the conductors mainly depend on their construction. Such construction was chosen where the standard (EN 50182:2001) gives the same calculated elastic modulus.

1.2. Test methods

The elastic properties of the conductors are described by the stress-strain characteristics. This was measured by a horizontal tensile machine (max. load 30 kN) at QC Laboratory of FUX Co. according to the descriptions of EN 50182:2001 Annex C. The ends of the conductors were fixed by resin dead ends. The gauge length was designated at a stress level of 5% of the rated tensile strength (RTS). The conductor was loaded from 5% of RTS to 30% of RTS and this load was held for 30 minutes. The loading rate was set to reach this force level within 2 minutes. After the 30 minutes, the conductor was released to 5% of RTS. After releasing the conductor, it was loaded immediately by 50% of RTS and hold this force level for 60 minutes. This last step (release and load) was repeated at 70% and 85% of the RTS force level. Finally, the conductor was released to 5% of RTS. The force and elongation values are continuously registered. At the evaluation stage, the elongation values belonging to the end of the load of the given force levels are used. This value contains the effect of short-term creep next to the elastic behaviour *(Figure 1)*.

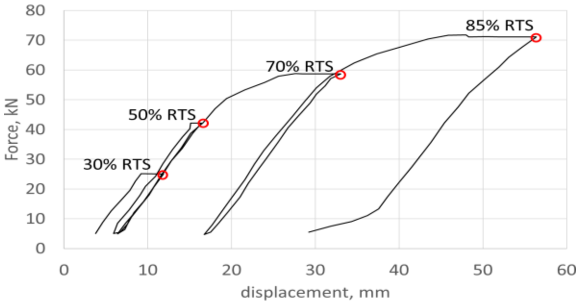

Figure 1
Stress-strain curve of the type I reference conductors without any heat treatment. The denoted point shows the force-displacement values which are used to calculate the stress-strain polynomials.

According to an old terminology it is possible to determine the slope of the linear sections of the releasing part of the curves. These values are possible elastic moduli, and these can be used in simple sag calculations. Nowadays a polynomial is fitted to the end points of the different force levels which are denoted at *Figure 1*. The application of this polynomial allows more accurate sag calculations.

During the operation, AC current (50 Hz) is heating up the conductor. It was simulated by a high current tester at the QC Laboratory of FUX Co. The temperature of the conductor was measured by thermocouples (K type) at two points. The thermocouples were placed between two wires in the outer layer of the conductors. During the heating process, the conductors reached the desired temperature level within 20 minutes. Then the conductors held that current i.e. temperature level. The conductors were cooled from the set temperature in the laboratory atmosphere. The cooling of the conductors took a maximum of 30 minutes. The heat-treatment plan is contained in *Table 2*.

Table 2
The heat-treatment plan of the tested conductors

Number	Conductor type	Treating temperature (°C)	Treating time (Hour)	Initial gauge length (m)
1	III.	230	3	9.13
2	III.	400	0.5	8.11
3	II.	400	0.5	10.10
4	I.	230	3	10.30
5	I.	400	0.5	7.68
6	II.	230	3	6.85

The calculation of the RTS value needs the tensile strength data of the wires of a given conductor. Therefore, after the treatment, a sample was taken from each conductor and the tensile strength of the wires were tested.

2. RESULTS AND DISCUSSION

Manufactured conductors without any treatment were also tested as a reference. The polynomials of the registered endpoints of the load cycles are plotted in *Figure 2*. The elastic moduli of the different conductors are calculated from the release sections of the stress-strain curves, but the polynomials are used in the accurate calculation of sag values in different spans. As mentioned, if the elastic moduli of the chosen conductors are close together, the polynomial shows the real difference in the behaviour of the conductors. The elastic moduli depend on mainly the construction of the conductors. *Figure 2* shows that the polynomial function strongly depends on the materials and states of the wires. So, this polynomial function will be used to show the effect of the heat treatments.

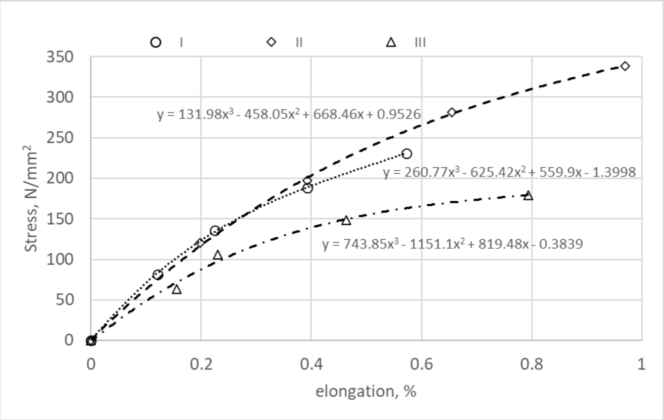

Figure 2

Stress-strain polynomials of the reference conductors without any heat treatment

Two types of treatments were performed. One type was made at 230 °C 3 hours. This temperature is the maximal operating temperature of the conductors of AT1. This heat treatment in case of wires is the standard heat resistivity test. Only a 10% loss of tensile strength is acceptable. This treatment was done for all other conductors for comparison.

The other type meant 400 °C for 0.5 hours. This is the temperature of another heat resistivity test. The acceptance criteria in case of AT1 are the same as was introduced before. Such a high temperature could form in case of an emergency. Both treatments are interesting for the evaluation of heat resistivity.

Heat resistivity could not be defined for conductors I and II, but the annealing of the wires modifies the strength values, hence the polynomials and the sag value. This knowledge in these cases is important due to the clearance.

Figure 2 shows that at the same elongation, conductor II has larger stress values than conductor I. Conductor II has a larger RTS value because of the fact that AL4 and ST6C wires have a larger tensile strength than AL1 and ST1A. The tensile strength of AT1 wires is close to the AL1 but the strength of the A20SA wires is less than ST1A, therefore, smaller stress values belong to the same elongation in the case of conductor III. The maximum elongation is determined by the elongation after the breaking of the wires. This value is around 1% in case of AL1 wires, 2-3% in case of AT1, and more than 4% in case of AL4 wires.

As a result of the heat treatments, the annealing of the AL1 wires started. The wires started to lose their strength. Therefore, the rated tensile strength became smaller after the treatments. The larger the temperature of the treatment is, the larger the strength decrement will be. This is not a surprising result; this can be derived from the annealing behaviour of the aluminium wires themselves. The effect of the temperature on the tensile strength is much larger than the effect of the soaking time. This is due to the well-known exponential dependence between self-diffusivity and temperature. The polynomials of conductor type I are shown in *Figure 2*. If the same elongation values are seen, lower stress values will be obtained after the treatments. The above analysis explains that the stress values after 400 °C at 0.5 hour are the smallest. Here, the elongation values belonging to the last point do not show any additional information, because different RTS values are used according to the tensile strength of the different wires.

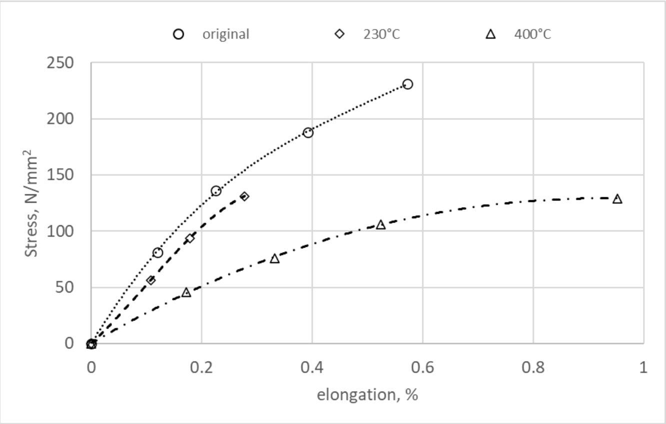

Figure 3
Stress-strain polynomials of the conductor type I (ACSR 264-AL1/34-ST1A)

Figure 3 shows the stress-strain polynomials of the heat-resistant HTLS conductor, type III. The comparison of *Figure 2* and *Figure 3* clearly indicates the heat resistivity of the conductor type III and its extent. The nature of the polynomials is the same, and the stress values belonging to 400 °C, 0.5 hour are also smaller than the stress values measured after 230 °C, 3 hours treatment. This comes from the RTS difference between the conductors. At a small stress level, there is minimal difference between the values. Normal stress applied at installation is 20% of RTS. For larger than 30% of RTS, the difference between stress values of the two different treatments starts increasing. The difference in the values of the reference conductor test is halved in case of conductor type III compared to type II below 30% RTS *(Figure 4)*. This relation remains true in case of 400 °C, 0.5 h treatment at larger force levels. But it becomes a small difference between the values of reference and the 230 °C, 3 hours of treatment. This shows that the sag value only slightly changes during the high-temperature operation.

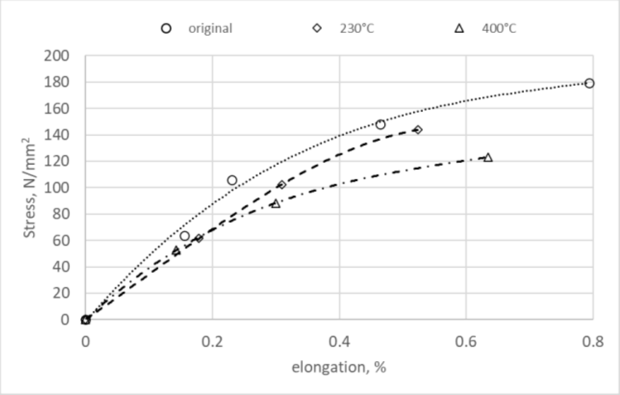

Figure 4
Stress-strain polynomials of the conductor type III (AACSR 264-AT1/34-A20SA)

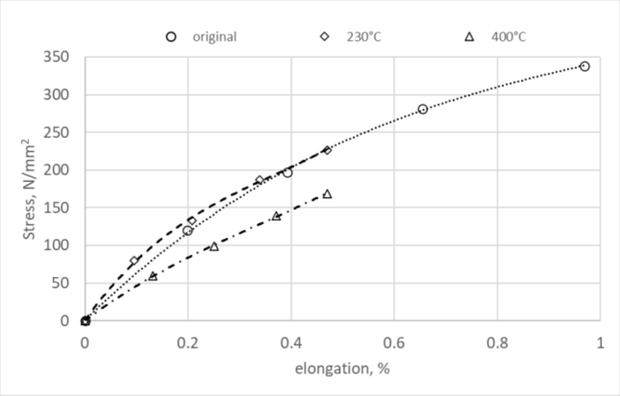

Figure 5
Stress-strain polynomials of the conductor type II (AACSR 185-AL4/43-ST6C)

Surprising results can be seen in *Figure 5*, which shows the result of the stress-strain polynomials of the conductor type II. Originally there is no heat resistivity in case of the AL4 wires. But there is no difference between the polynomial of the original conductor and the one treated at 230 °C, 3 hours. The EN AW 6101 alloys are heat-treatable and 230 °C is the maximum temperature range of aging treatment. Additionally, ST6C wires have the largest strength. These two facts cause this phenomenon. The loss of strength in this case is half of what was measured in conductor type I at 400 °C, 0.5 hour. This is not a real heat resistivity, it originated from the strength and the type of alloys, but the effect on the sag value is nearly the same. It is necessary to know that this type of conductor is typically used as a protective conductor against lightning, so in normal operation, there are no current flows on this conductor. But the emergency case is possible.

To compare the conductor types after the treatment at 400 °C, 0.5 h, the same sequence can be evaluated without any treatment. But at 230 °C, the stress values of conductor type III are larger than type I. This shows that at elevated temperature, which is the upper limit of the heat resistivity of AT1 wires, the mechanical performance is better for the examined HTLS conductor type. This can be explained by the annealing behaviour of the AT1 wires. While the AL1 wires are fully annealed by this treatment, the recrystallization and recovery do not start in the AT1 wires. Just a small recovery could be taken into account with a maximum 10% tensile strength decrement of the AT1 wires.

CONCLUSION

Three ACSR type conductors are compared, related to heat resistivity. A normal AL1/ST1A phase conductor, an HTLS type AT1/A20SA phase conductor, and a protective conductor type AL4/ST6C. All of them have an application advantage. In normal conditions, the Al1/ST1A phase conductors have the largest current carrying capacity. But the HTLS conductors, due to the heat resistivity, provide a larger current carrying capacity at elevated temperature with low sag values. AL4/ST6C conductors have the largest strength, so they can be used at large span lengths, too. But this type has the largest resistivity.

The heat resistivity of the mentioned conductor types was compared through the test of the elastic behavior. The heat resistivity of the conductors is in relation to the material and the state of the aluminum and steel wires. The largest change in mechanical properties happens in the aluminum wires at elevated temperatures, of course. But it is better to handle the whole conductor together. Therefore, the stress-strain polynomials were compared in the article because the elastic moduli of the conductors are mainly determined by their construction, not the material properties.

Two types of treatments were applied: 230 °C, 3 hours, which simulates a high-temperature operation, and 400 °C, 0.5 h, which simulates emergency conditions. The effect of the treatments on the stress-strain polynomials clearly shows the heat resistivity of the HTLS construction compared to the normal AL1/ST1A phase conductor. But the AL4/ST6C conductors show a surprising effect. There is just a small change in the stress-strain polynomial between the reference and the 230 °C, 3 h treated conductors. Additionally, minor change can be observed after 400 °C, 0.5 h compared to the results of HTLS conductors. The cause of these results is that the ST6C wires have the largest tensile strength, and AL4 wires are heat treatable. But it is necessary to take into account the large resistivity of this type, as it is rarely used in phase conductors due to its large loss.

ACKNOWLEDGMENT

M. Sepsi contributed with the professional support of the Doctoral Student Scholarship Program of the Co-operative Doctoral Program of the Ministry of Innovation and Technology financed by the National Research, Development, and Innovation Fund.

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