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Research of the Artificial Ageing Parameters Effect on Low-Temperature Creep of AlMgSi Wires

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The hardened-precipitation type alloys AlMgSi grade 6101 of 0.5% Mg and 0.5% Si contents, are used for the construction of homogenous wires in overhead power lines. The suitability of these alloys lies in the characteristics of their electrical and mechanical properties within a wide range of heat treatment. Since alloys of this kind must meet certain standards with regard to creep resistance, the parameters for artificial ageing have to be controlled during the production process, in order to guarantee the appropriate rheological resistance. Therefore it is essential to define the impact of the separation fixing quantity on the material's susceptibility to creep resistance.
This paper presents the test results of the artificial ageing parameters on the creep characteristics of wires made of AlMgSi alloy produced from wire rod of T4 state, manufactured with the use of Continuous Properzi technology. The results enable us to formulate the duration of the artificial ageing process to achieve the required creep parameters of AlMgSi wires.

Keywords: *low temperature creep, AlMgSi, overhead power lines, rheological properties, precipitation hardening.*

1. Analysis of the subject matter

The global increase in demand for energy, and hence in transferred power, may lead to power line overloads and, consequently, in cascade outages of power supply systems, so called blackouts. This determines trends prevailing in the power industry, the mainstream of which consists in permanent search for solutions that lead to possible increases in transmitted power. Limited capacity of new power line procurement resulting from high costs and current building law is the cause for the search for cheaper alternative solutions. Most often existing power lines are upgraded by way of their rewiring with higher ampacity conductors. An effective approach to the subject issue is the application of homogenous wire designs that make the whole conductor section electrically active with no need to change its sizes. In addition such design guarantees uniformly distributed wire effort in each layer and eliminates internal stress resulting from the difference of the material's thermal expansion coefficients.
According to standard PN-EN 50183: 2000 (Overhead power line conductors – Bare conductors of aluminium alloy with magnesium and silicon content) [1] the following seven types are distinguished of wires for overhead line conductors (types A12 – A18). Figure 1 presents a graphical rendering of the said standard's requirements. It may be noted that depending on their electrical resistivity the wires may be categorised in the following three groups: (i) low resistivity (30 nΩm), (ii) medium resistivity (31 nΩm), and high resistivity (32.5 – 32.8 nΩm). Tensile strength of these wires with 1.5 – 5 mm diameters amounts to 245–342 MPa [1].
The standards require the use of wire rod grade 6101 or 6201 after homogenisation, solution treatment in furnace and natural ageing (T4 treatment). In other countries AlMgSi wires are used that are based on similar content of the basic alloying components. Differences between them are in the initial stage and the wire rod to wire processing technology only. IEC standards that provide for requirements of wire rod, wires, and conductors, do not concern details of the alloys' chemical

composition [3-4]. The objective is in obtaining such ultimate properties of the end product (wire, conductor) that meet the standards' recommendations [1-2].

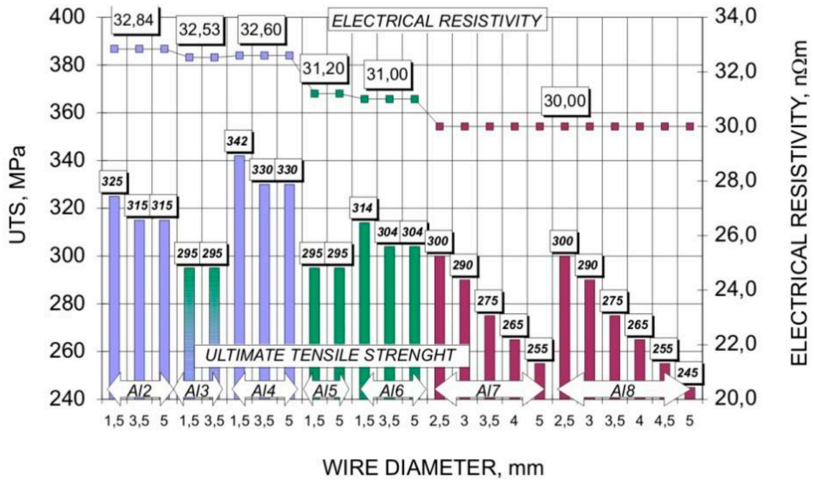

Fig. 1 Minimum tensile strengths and permissible resistivity of AlMgSi wires according to EN 50183:2000 [1]

It is similar concerning conductor wires' rheological properties. The alloy wire creep occurs in a temperature equal to or less than 100°C (homological temperature < 0.15) at average annual stress (Every Day Stress) equal to 20% UTS (Ultimate Tensile Strength) and the permanent conductor elongation during ten years below one per mille. The foregoing properties are of high practical relevance, since they cause an irreversible drop in the wire's longitudinal stress from 20 to 40 MPa depending on the span length, which translates into larger sag and the risk of electrical breakdown to earth [5].

Research conducted by such world's leading centres as IEEE, CIGRE, EPRI, Alcoa, Reynolds Metal Aluminium, Furukawa Electric, BPA, and Ontario Hydro for identification of the wire and conductor creep, creep modelling, and determination of basic recommendation and operating constraints have enabled development of the ten year permissible creep in the range of 0.5 per mille [3]. This constraint refers to all types of alloy and aluminium/steel conductors. For a conductor of an uniform design and made of aluminium wires the ten year permissible creep amounts to 0.8, while for aluminium/alloy wires to 0.7 per mille [5].

The creep intensity (wire's susceptibility thereto) depends on the wire material's properties. In the event of low-temperature processes, whereby the atomic thermal vibration energy is low compared to the creep activation energy, thermally activated processes do not occur at all or only partially. Therefore creeping in low temperatures results from dislocation regrouping only. The most common theory describing the low-temperature creep mechanism is so called Nabarro-Mott's exhaustion theory [6] that attributes decreased creep speed to decreasing densities of movable dislocations that are anchored on barriers (grain limits, inclusions) and due to insufficient thermal fluctuations are not capable of climbing, which means that they stay on their slide surfaces.

The following function is commonly considered a phemenologic model of the process of low-temperature creep of aluminium and aluminium alloy wires:

$$\varepsilon_p = f_1(\sigma) \cdot f_2(T) \cdot f_3(\tau) \tag{1}$$

where:

$$f_1(\sigma) = \sigma^n \tag{2}$$

$$f_2(T) = e^{\varphi T} \tag{3}$$

$$f_3(\sigma) = \tau^{\beta} \tag{4}$$

Upon additional consideration of the multiplicative constant:

$$\varepsilon_p = \alpha_0 \sigma^n e^{\varphi T} \tau^{\beta} \tag{5}$$

σ, T, τ - stress, temperature and duration of the process,
n, ϕ, β - material constants
α_0 - parameter.

The appropriateness of selection of functions describing the effect of stress, temperature and time is experimentally verifiable. Parameters n, ϕ, β and α_0 are unknown, their approximations are looked for based on measurement of σ, T, τ and ε_p. The relationship between them is non-linear; however this model may be simply converted into a linear model by finding the logarithms of the both sides of the equation (5). Then we receive:

$$ln(\varepsilon_p) = ln(\alpha_0) + n ln(\sigma) + \varphi T + \beta ln(\tau) \tag{6}$$

It is easy to conclude based on analysis of function (5) that the higher the values n, ϕ, β and α_0 coefficients, the larger shall be the creep deformation under given conditions σ, T, τ. For a given material coefficients n, ϕ, β are constant and depend on, among other factors, chemical composition selection, strain hardening, thermal treatment conditions, etc. Table 1 presents examples of the creep function for aluminium wires made of a wire rod manufactured by continuous casting and CP rolling, and Figure 2 shows their graphic illustration [6].

Table 1. Mechanical properties and parameters of aluminium wires creep function

Diameter [mm]	UTS [MPa]	α_0 x10^{-6}	n	φ	β	source
2.5	180	277	1.35	0.025	0.210	[6]
3.5	165	264	1.35	0.025	0.200	
4	155	142	1.40	0.025	0.170	

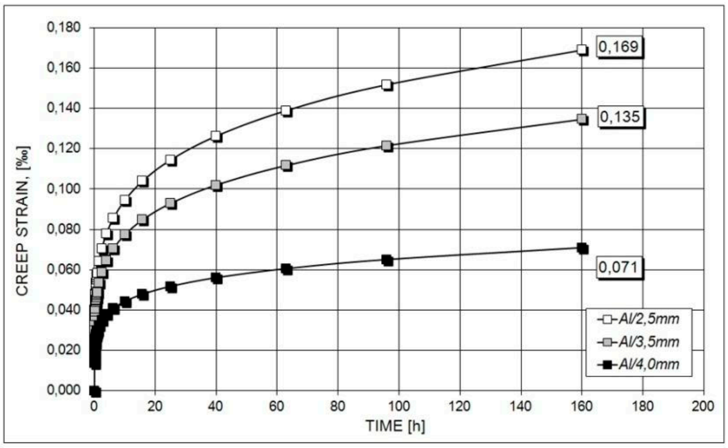

Fig.2. Creep characteristics of aluminium wires, creep conditions: temperature– 20°C, stress – 20% UTS, time – 160 h (comp. Tab. 1).

It should be observed that smaller diameter wires are also less resistant to creep, which results from higher strain hardening of thin wires, and from the creep process dislocation mechanism. This

observation concerns aluminium wires. A question therefore arises of a similar property with respect to wires made of the hardened-precipitation type alloys AlMgSi, whereby strain and precipitation hardenings interact. It may be expected that alloy wires' rheological resistance depends on the relation between their strain and precipitation hardenings, and also on phase morphology. Because regarding the subject alloy, product properties' development is feasible through skilful combination of the classic strain hardening with the hardening effect of dispersion phase, the limiting solubility in aluminium, which amounts to 1.85%. A parameter that modifies mechanical effects of the both hardening types is the wire rod's initial condition and the natural ageing duration prior to the drawing process. A wire's final properties may be ultimately determined through low-temperature thermal treatment. Depending on temperature and ageing duration the material properties may be controlled over a wide range of their variability [5-7].
Based on the analysis of the rheologic problem with regard to AlMgSi wire alloys conducted in previous chapters, the following issue was subject to experimental verification:

How AlMgSi wires heat treatment parameters affect their susceptibility to rheological processes?

2. Research programm and material

Wires made of AlMgSi 6101 grade were selected for the research. Details of the alloy's chemical composition and wires properties are presented in the following table.

Table 2. Material characteristics of AlMgSi wire for creep tests

Wire No	Diameter [mm]	Alloy grade	Chemical composition [%]				Temper	UTS [MPa]	Elong. A_{250} [%]	ρ [nΩm]
			Mg	Si	Fe	Ti [ppm]				
1	2.90	6201	0.57	0.57	0.25	30	After drawing	290	4.1	34.40
2	2.90	6201	0.57	0.57	0.25	30	After heat treatment (155°C/4h)	340	4.6	32.29
3	2.90	6201	0.57	0.57	0.25	30	After heat treatment (155°C/ 14h)	340	5.0	32.12

The subject wires were made of wire rod and subjected to T4 temper (homogenised, solution treated from furnace, naturally aged). Wires selected for the creep process research were first drawn (wire no 1) and then artificially aged in 155°C for 4 h (wire no 2) or aged in 155°C for 14 h (wire no 3).
Tests on the creep process were carried out in a specialized isothermal chamber on the wires with the diameter of 2.90 mm subjected to the condition of uniaxial tension. Displacement parameters' were measured with the use of 1 μm graduated dial indicator. The creep test comprised: placing the wire in the chamber, additionally equipped with the system of mechanical compensation of temperature fluctuations influence during the test; stabilising the temperature inside the chamber (and on the wire); gravitational loading of the wire with weights of precisely specified mass; and systematic measuring of the length increases on the wire with the base of 1 000 mm (1m).

3. Study results and their analysis

Based on the creep research three creep functions were obtained that are presented in the following table 3. The functions describe the process of AlMgSi wire creep under stress up to 34-136 MPa and in temperatures 0-80ºC.

Table 3. Mechanical properties and creep function parameters of AlMgSi and Al wires

Wire no	Creep functions	α_0 x10^{-6}	n	φ	β
1 (after drawing)	$\varepsilon_p = 0{,}0000102 \cdot \sigma^{1{,}89} \cdot e^{0{,}021T} \cdot \tau^{0{,}021}$	102	1.89	0.021	0.260
2 (heat treatment)	$\varepsilon_p = 0{,}00000717 \cdot \sigma^{1{,}85} \cdot e^{0{,}021T} \cdot \tau^{0{,}021}$	7.17	1.85	0.021	0.209
3 (heat treatment)	$\varepsilon_p = 0{,}0000115 \cdot \sigma^{1{,}26} \cdot e^{0{,}021T} \cdot \tau^{0{,}020}$	115	1.26	0.020	0.206

Detailed analysis of the wire creep function, and of n, φ, β and α_0 in particular, substantiates the statement that with regard to the alloy wires coefficient φ and β may be assumed constant, whereas n and α_0 feature a wide dispersion. The first observation is that wires after undergoing drawing process are characterized by the lowest rheological resistance. It results from the fact that it is a deformed material of high dislocation density which is favourable for creep (creep dislocation mechanism). On the other hand wires after artificial ageing are more rheologically resistant (see Table 3 and Figure 3).

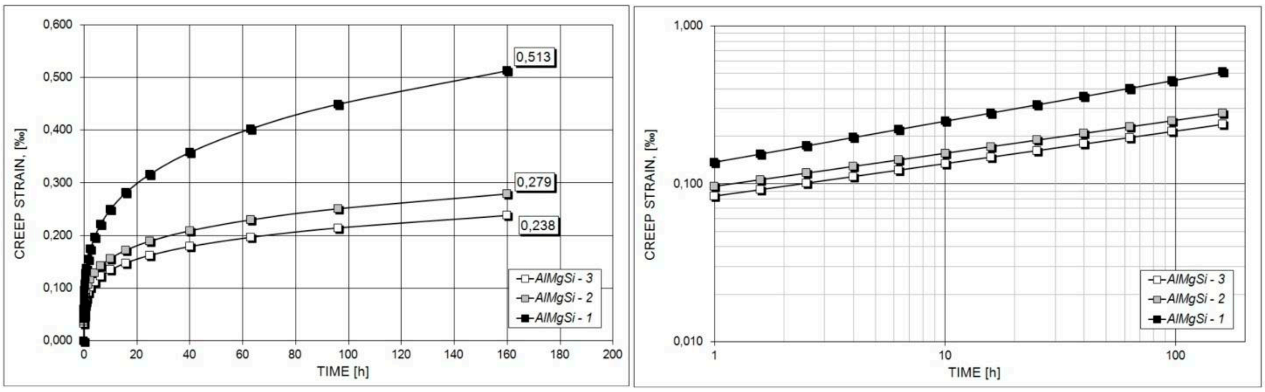

Fig.3. Creep profiles of AlMgSi wires obtained in temperature 20ºC and under stress 40% UTS, during 160 h of the process.

Even if from the point of view of their properties the wires are identical, still their rheological response is completely different. In view of the foregoing observation, and additionally, of the fact that the AlMgSi wires in the variants (2 and 3) represent a material with the same mechanical properties, looking for an answer to the following question seems interesting:

"which of the foregoing creep functions is more advantageous, i.e. describes the more creep-resistant material ?"

It has been found that the answer to this question is not unambiguous. Because creep distortion of the subject wires significantly depends on conditions (stress and temperature) of the creep process. The following figure presents the wires' creep profiles obtained under the following conditions: temperature – 20ºC, stress 20%UTS (68 MPa), 30% UTS (102 MPa) and 40%UTS (136 MPa) creep test duration – 160 h. It has been found that the wires' rheological responses vary depending on stress duration.

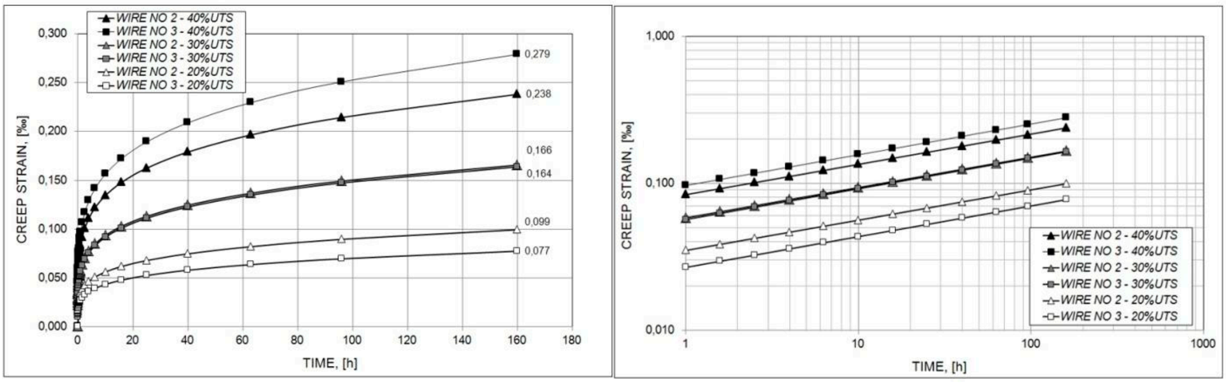

Fig.4. Creep profiles of AlMgSi wires (2 and 3) obtained in temperature 20ºC and under stress 20, 30, and 40% UTS, during 160 h of the process.

Under 68 MPa stress the 2 wire's creep was less intense than that of wire 3, whereas under high stresses the response is opposite. Under 30% UTS (102 MPa) stress the functions became identical, i.e. they both ultimately lead to the same creep distortion. Whereas higher stresses induced the opposite response. The reason for it is the stress power coefficient for wire 2 function amounts to 1.85, while for wire 3 function – 1.26.

4. Acknowledgements

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5. Conclusion

1. It has been indicated that low temperature creep of precipitation-hardenable AlMgSi alloy wires can be described by power stress and time function and exponential function of temperature.
2. AlMgSi wires being directly after the process of drawing have the lowest rheological resistance than wires after artificial ageing.
3. An increase of artificial ageing time of wires made of AlMgSi alloy causes the rise of material rheological resistance.

7. References

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