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POLSKA AKADEMIA NAUK

Arch. Metall. Mater., Vol. 61 (2016), No 4, p. 1875–1880

DOI: 10.1515/amm-2016-0302

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NEW Al-Ag ALLOYS FOR ELECTRICAL CONDUCTORS WITH INCREASED CURRENT CARRYING CAPACITY

The paper shows a new idea of aluminium alloys. New alloys with specially selected alloying element i.e. silver have electrical conductivity similar to pure aluminium at ambient temperature and better than pure aluminium electrical conductivity at increased temperatures. Al-Ag alloys for electrical applications (mainly for electrical conductors) due to high electrical conductivity at increased temperatures at the level of the maximum conductor working temperatures give possibility of better current capacity of conductors.

The experimental results of basic mechanical properties and the electric conductivity versus temperature relation are shown in the paper as well as examples of the tested material operational properties.

The summary gives theoretical analysis based on examples of the potential applications of Al-Ag alloys (new conductor designs) which provide the benefits of the new solutions in comparison to traditional conductors.

1. Introduction

Many Al-Ag alloys are well known objects of scientific studies years due to Guinier-Preston zones formation. This phenomenon for example was discussed in an early paper of Guinier [1], next Borelius work [2] and today researches [3]. Main object of research are mechanisms and morphologies of phases precipitations from the solid solution during the heat treatment i.e. researches are focused on multiphase materials. It is believed that in Al rich Al-Ag alloys the precipitation sequence consist the solid solution, Ag atom clusters, GP zones, γ' phase and equilibrium γ (Ag_2Al) phase. Clusters and GP zones have the spherical shape, γ' and γ phases are hexagonal with different lattice constants. Widmanstätten type structure is often observed in Al-Ag alloys after ageing [4]. Beside fundamental microstructural analysis some scientific papers describe Al-Ag macroscopic properties like electrical conductivity, Young modulus, mechanical properties, etc. [5], [6].

Practical usage of Al-Ag alloys is very limited due to relative high Ag prices in comparison to other typical alloying elements in aluminium alloys. The paper gives the analysis of the low silver content Al-Ag alloys uses in electrical applications, mainly for electrical conductors, which can be economically reasonable.

The Ag-Al phase diagram detailed analysis shows the eutectic transformation at the 840K (567oC) temperature in the Al rich area [7]. Ag in Al solubility in the solid state is high (up to the 56%) at the eutectic temperature. The solvus line on the Al side in the Ag - Al phase diagram is not sufficiently understood and there is the significant dispersion of the solubility results obtained by different authors. Overview of the experimental results of the solvus line prediction can be found in [7], [8]. Generally due to the actual knowledge it is believed that the solubility of Ag in Al at 370K (100oC) vary from 0,2%mas - 0,8%mas. Precipitous solvus line shape in Ag-Al system gives the hypothesis that Al-Ag alloys up to 0,1%mas Ag are single phase solid solution at the electrical conductors working temperatures range. The maximum temperature difference in L-S state is about 40K at the ~40% Ag and liquidus and solidus lines in the Al-Ag phase diagram shows that the equilibrium distribution coefficient is much lower than one. This gives the risk of the high chemical composition segregation. On the other hand at small Ag content (up to 0,1%) solidus and liquidus are close to each other that recede the segregation.

Al and Ag crystal lattices and atoms diameters are very similar. As a consequence Ag easily dissolves in the Al in the solid state. Due to discussed similarities the Al electrical conductivity decrease with Ag addition is not high and the solution strengthening resulting from the presence of Ag atoms in Al matrix is not significant. This gives the possibility to obtain alloys with excellent electrical properties, better performance characteristics and similar to pure aluminium mechanical properties.

2. Materials and experimental procedures

Al-Ag alloys with 0,1%mas. Ag, 0,25%mas. Ag and 0,54%mas. Ag content and pure Al as a reference material samples were synthetized in the first step of the research to analyse Ag content effect on the material electrical conductivity decrease. High purity 99,99%mas. Al and 99,99%mas. Ag base metals were used. Both metals were melted in tight graphite crucibles at the 1023K (750°C). After melting liquid metals were stabilized for 1h, mixed, stabilized for 1h, mixed, stabilized for 0,25h and solidified. Next samples were cut form

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solidified billets. Material electrical conductivities at ambient temperature were measured on the samples. After that samples were homogenised at 873K/100h (600°C/100h) and quenched to water. Electrical conductivity measurements were done and samples were cold deformed (total strain 80%) followed by the final electrical conductivity measurements.

Al-Ag alloys with Ag content up to 0,1%mas. were synthetized in the second research step. EN AW 1350 and EN AW 1370 (i.e. min. 99,5%-99,7% commercial purity aluminium) are often used for electrical conductors. For the advanced applications sometimes 99,85% purity Al is used and samples for the tests was prepared from this grade material. Main Al contaminations: 0,1%mas Fe 0,04%mas Si and Cu, Mg, Mn, Zn trace level. Heavy elements (V, Ti, Zr, Cr) content were controlled to provide high electrical conductivity. 99,99%mas Ag was used too.

The 10mm diameter rods were cast form 0,025%mas. Ag (AlAg0,025), 0,050%mas. Ag (AlAg0,05), 0,10%mas. Ag (AlAg0,1) Al-Ag alloys and reference materials (99,85%mas. Al). All materials to test were prepared by the same procedure like in the first step of research.

Electrical and mechanical properties were measured for as cast and homogenised materials and next 3mm diameter wires were prepared by cold drawing (total strain 91%). Tensile tests and stress relaxation tests were performed on the wires in the hard drawn temper. Softening behaviour of selected materials (Al and AlAg0,1) were analysed too.

Identification of tested materials electrical properties as a function of the temperature was the key part of the research. This allows to calculate current carrying capacity of conductors fabricated from tested materials. To perform those tests wires were heated up with 20°C intervals and resistances were measured. The increased temperature resistance and the ambient temperature resistance ratio versus the temperature increase relationships were done and temperature coefficients of resistance were calculated by the linear approximations.

On this basis the theoretical analysis of the Al-Ag alloys application as electrical conductors were performed.

3. Research results and analysis

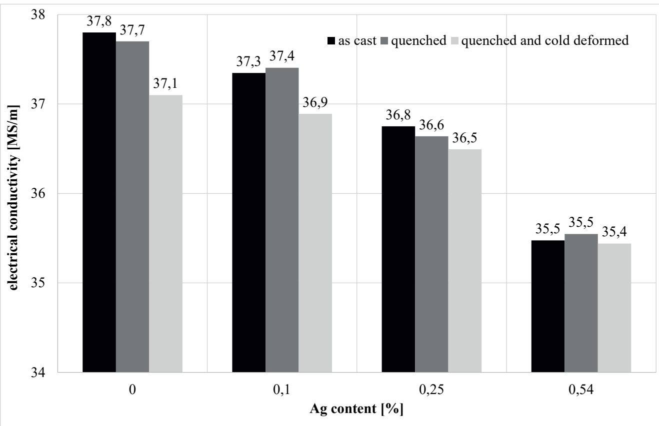

Fig. 1. Ag content effect on the ambient temperature electrical conductivity of Al-Ag alloys. Materials prepared from 99,99%mas purity base metals

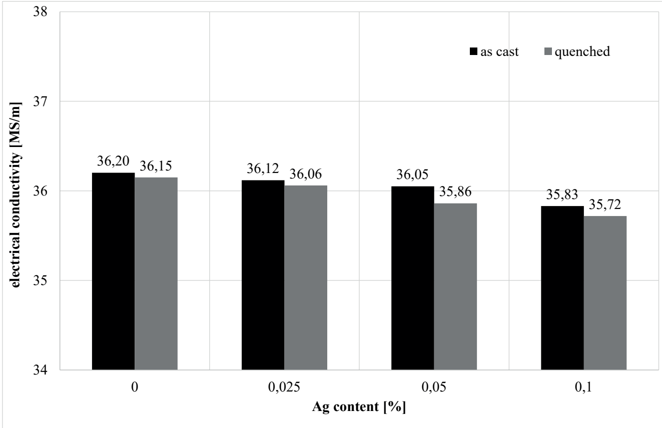

Fig. 2. Ag content (in the range 0,025mas. % to 0,1%mas) effect on the ambient temperature electrical conductivity of Al-Ag alloys. Materials prepared from commercial purity aluminium used for electrical applications

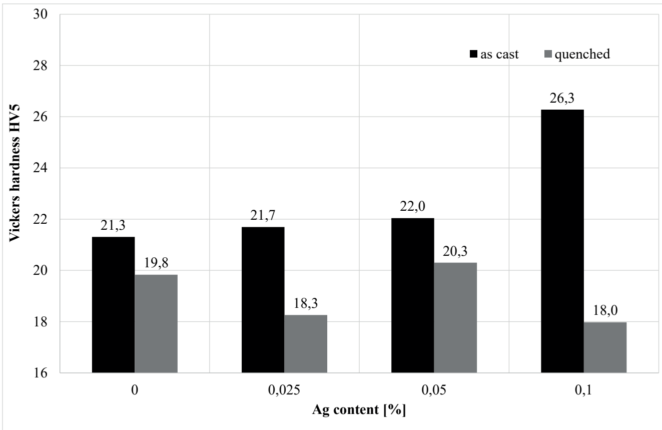

Fig. 3. Vickers hardness of Al-Ag alloys (with Ag content up to 0,1%mas.) in different tempers

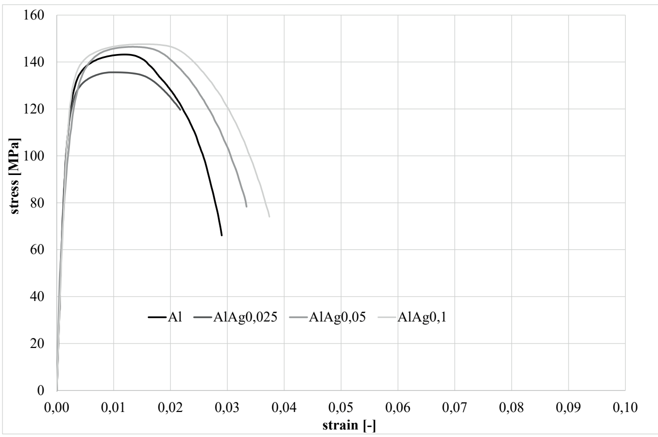

Fig. 4. Tensile tests of the Al and Al-Ag alloy wires after cold drawing (total strain 91%)

Fig. 1. shows Ag effect on Al-Ag alloy electrical conductivity (alloys prepared from high purity raw materials during the first step of the research). Electrical conductivity of materials in the as cast temper and after homogenisation and quenching are similar. This suggest that in all analysed cases Ag atoms locate mainly in Al solid solution. Materials after cold deformation exhibit slightly lower electrical conductivity

due to defects accumulation during the deformation. The electrical conductivity of the material is roughly linear function of Ag content in the alloy. This agrees with Nordheim's rule. 0,43MS/m per 0,1%mas. Ag in the as cast temper and 0,41MS/m per 0,1%mas. Ag in the homogenised and quenched temper electrical conductivity decrease is observed. The measurements correspond quite well with literature data [9]

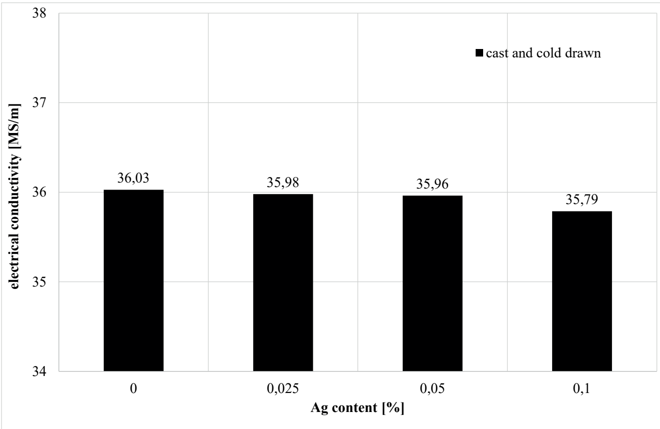

Fig. 5. Ambient temperature electrical conductivity of the Al and Al-Ag alloy wires after cold drawing (total strain 91%)

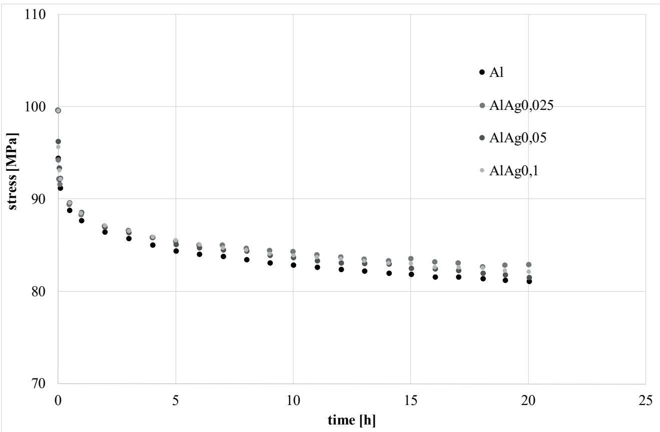

Fig. 6. Stress relaxation (tensile) tests of Al and Al-Ag alloy wires after cold drawing (total strain 91%). Initial stress 100MPa, temperature of test 293K (20°C)

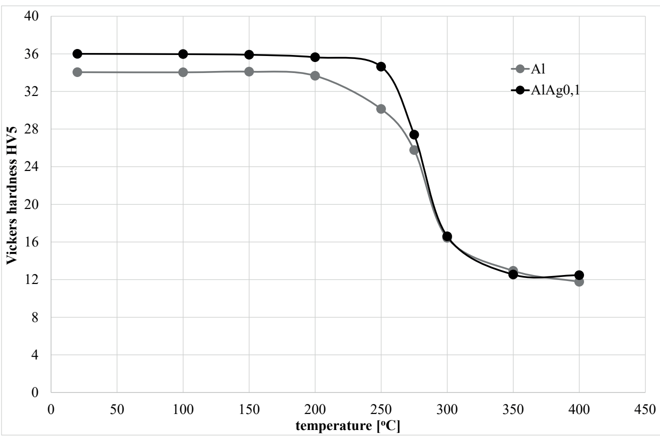

Fig. 7. Softening of Al and AlAg0,1 measured by Vickers hardness changes as a function of heating temperature, hardness measurements at ambient temperature after heating and cooling

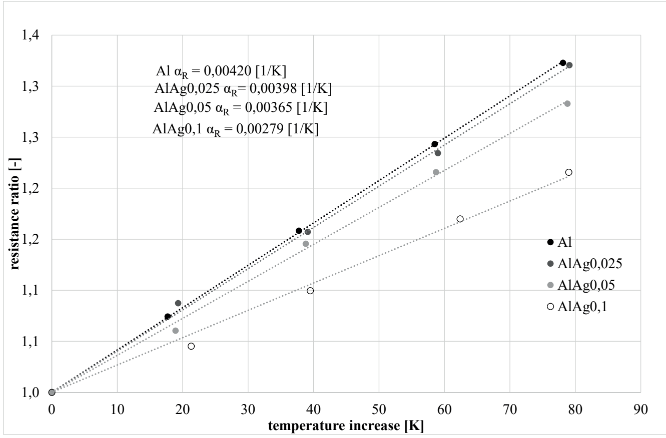

Fig. 8. Al and AlAg wires electrical resistance change as a function of temperature - resistance at increased temperature to resistance at ambient temperature ration versus temperature increase

Similar results of the Ag content at the level up to 0,1%mas. impact (in aluminium technical purity materials for the second stage of the research) on the material electrical conductivity are depictured on fig. 2. The homogenisation and quenching process does not affect significantly the electrical properties but a small decrease in the conductivity after quenching is clear. The observed difference of pure Al and AlAg0,1 electrical conductivity is 0,40MS/m - 0,43MS/m. This is similar to the case of materials made from high-purity elements. The results show clearly that 0,1%mas. Ag addition to Al of reduces the electrical properties of the material about 1%.

The as cast and quenched material hardness can be found on fig. 3. The Ag addition causes in small but clear Vickers hardness increase in as cast temper. It can be result of solution strengthening or grain size. Solution strengthening probably is not a key factor due to fact that after quenching hardness is almost equal in all analysed materials.

Tensile tests of the hard drawn wires are shown on fig. 4 while electrical conductivities on fig 5.

The difference in the tensile strength of tested materials in hard temper is below 5% which suggest that Al-Ag alloys with Ag content up to 0,1%mas Ag are quite similar to pure aluminium. Higher than for pure Al elongation to break during tensile test for AlAg0,05 and AlAg0,1 alloys are observed which may suggest higher formability of discussed alloys. Differences in the electrical conductivity between the studied wires are lower than in cast or quenched materials (see fig. 5). Rheological resistance (measured by the stress relaxation during tensile testing tests) of Al-Ag alloys is similar to pure Al (see fig. 6).

Addition of 0.1%mas. Ag to Al increases the initiation of the recrystallization temperature about 50K. It can be an important advantage of the Al-Ag alloys in electrical applications because the increase operating temperature range is possible when hard drawn temper wires are used. The softening behaviour is shown on fig. 7.

The most important utilitarian aspects of the paper are the material electrical conductivity versus temperature measurements. Temperature effect on electrical conductivity is generally known. In the cryogenic temperatures the electrical conductivity of materials is usually constant and in the higher temperatures the electrical conductivity decrease with the temperature increase. The conductivity - temperature relationship is non-linear but in relative small temperature ranges can be successfully approximated via linearization. On this basis the temperature coefficient of resistance can be calculated from the slope of the line. Material electrical conductivity at ambient temperature and temperature coefficient of resistance are two main material constants which allow to conductor current capacity calculations.

Fig. 8. shows the temperature effect on the electrical resistance changes for tested Al-Ag alloys. The value of the temperature coefficient of resistance for pure Al is about 0,0042K^{-1}. The temperature coefficient of resistance decrease with Ag content increase in alloy: AlAg0,025 - 0,0040/K^{-1}, AlAg0,05 - 0,0037K^{-1}, AlAg0,1 - 0,0028/K^{-1}. In fact this coefficient differentiates strongly the tested materials. This is the key for the increasing of the current carrying capacity of conductors made form Al-Ag alloys.

4. Theoretical analysis of current carrying capacity of the conductors with AlAg alloy wires in relation to the traditional conductors with Al wires

The comparative analysis of the current carrying capacity of the conductors with AlAg alloy wires versus traditional conductors with aluminium wires example was prepared for the typical Hawk conductor (similar to polish AFL-6 240 conductor). The selected conductor is typical for the high voltage distribution lines (110kV, 220kV). The Hawk conductor has seven wire steel core and two layers of aluminium wires. Main Hawk construction details are shown in the tab. 1. Two options were analysed: conductors with wires in hard temper (hard drawn wires ACSR conductor) with nominal maximum operating temperature 353K (80°C) and conductors with wires in soft temper (soft - annealed wires ACSS conductors) with nominal maximum operating temperature 423K (150°C).

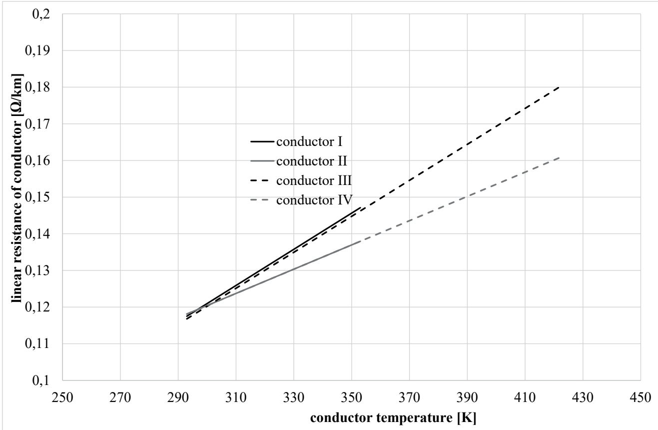

Fig. 9. Linear resistance of conductors from tab. 1 as a function of conductor temperature

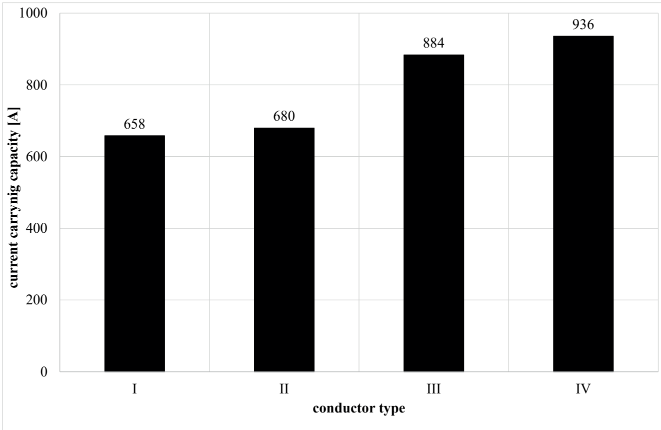

Fig. 10. Current carrying capacity of conductors from tab. 1 for maximum operating temperature; ambient temperature 293K (20°C), wind velocity 0,5m/s, solar radiation 900W/m^2

Linear resistance of analysed conductors design (see tab. 1) as a function of conductor temperature is shown on fig. 9.

TABLE 1

Design of analysed conductors

conductor type	I (ACSR)	II	III (ACSS)	IV
core material	steel wire	steel wire	steel wire	steel wire
core construction (no of wires in layers)	1+6	1+6	1+6	1+6
core wire diameter [mm]	2,67	2,67	2,67	2,67
core diameter [mm]	8,01	8,01	8,01	8,01
core cross section [mm^2]	39,2	39,2	39,2	39,2
external layers material	Al hard temper	AlAg0,1 hard temper	Al soft temper	AlAg0,1 soft temper
external layers construction (no of wires in layers)	10+16	10+16	10+16	10+16
external layers wire diameter [mm]	3,44	3,44	3,44	3,44
conductor diameter [mm]	21,77	21,77	21,77	21,77
external layers cross section [mm^2]	241,7	241,7	241,7	241,7
external layers material conductivity [MS/m]	36,0	35,8	36,2	35,8
factor of the resistance increase due to stranding [%]	2,2	2,2	2,2	2,2
linear resistance of conductor at ambient temperature [Ω/km]	0,1175	0,1181	0,1168	0,1181
temperature coefficient of resistance [1/K]	0,0042	0,0028	0,0042	0,0028
maximum operating temperature [K]	353	353	423	423

(ACSR – aluminium conductor steel reinforced, ACSS - aluminium conductor steel supported)

All analysed conductors have similar electrical properties at ambient temperature but at maximum working temperature there is significant difference in calculated resistances. Conductor with AlAg0,1 wires in hard temper at 353K (80°C) shows more than 6% lower electrical resistance than conventional ACSR with Al wires. Conductor with AlAg0,1 wires in soft temper at 423K (150°C) shows more than 10% lower electrical resistance than conventional ACSS with Al wires. As a consequence of attractive resistance at maximum working temperature conductors with AlAg wires gives higher current carrying capacity. Nominal current carrying capacity of analysed conductors according to IEC 1597 standard [10] is shown on fig. 10. AlAg0,1 wires can increase capacity more than 20Amps at 353K (80°C) and more than 50Amps at 423K (150°C) which is about 6% increase without any changes within geometrical parameters of conductor.

5. Summary

AlAg alloys with low Ag content offer very attractive possibilities of the conductor current carrying capacity increase especially in the cases of ACSS conductors with soft wires which operates to 150°C -240°C. This useful effect is a superposition of the good electrical conductivity at ambient temperature and the low temperature coefficient of resistance. Fundamental macroscopic properties of AlAg alloys are similar to the pure aluminium and don't affect conditions of the conductor exploitation.

Acknowledgments

The paper presents research results were performed as a part of the project co-founded by The National Centre for Research and Development: INNOTECH-K2/IN2/29/182190/NCBR/13.

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