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Examination of the Impact of Additives Zirconium on the Heat Resistance of Conductive Aluminum Alloys

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Modern solutions in field of overhead conductor require aluminum alloys that are characterized by high temperature of continuous work up the level to 210°C. Obtaining required parameters of material work is possible on the metallurgic intervention by additions of rare-earth elements especially zirconium. Defining heat resistance of new alloys, that is setting long-term work temperature is not possible on the basis of traditional approach in the form of definition of recrystallization temperature. Proposed methods of defining long-term heat resistant general rely on typical mathematical methods of description and approximation of experimental studies results. In connection with above-mentioned, the main goal of the paper is to present researches on laboratory methods of defining material heat resistance. Wires from AlZr alloys with different quantity of alloy additions were exposed to examination. Presented in the paper method used Arrhenius plot allows for classification heat resistance of AlZr alloys destined for production of conductors type HTLS (High Temperature Low Sag).

Keywords: *heat-resistant aluminium alloys, aluminium-zirconium, electrical application*

1. Introduction

Using aluminium and its alloys for building power conductors results from their good electrical, mechanical properties, low mass density and economic reasons. Additionally materials used for wires for conductors must characterize with rheological, fatigue resistance, corrosive resistance and heat resistance. The last property results from the fact that during exploitation time strain strengthened wires transfer the conductor's tension power and in this connection one cannot allow to thermal degradation of their strength properties. Temperature of conductor's work results from the thermal balance and depends mainly on quantity of electricity transmission by power line in given atmospheric conditions. With this regard, defining acceptable work temperature of the material is the base for safe and trouble-free work of power line.

In 2004 in UST-AGH there has been started researches on elaboration of heat resistant aluminium-zirconium alloys destined for application in electroenergetics. In this connection, there has been started study over elaborating method of parametrization of researched materials at an angle of heat resistance. Traditionally accepted measure of heat resistance, especially technically clear metals, is recrystallization temperature. Most often it is defined as total removal temperature of results of strengthened material submitted to one-hour exposure. Assuming that conductor's time of exposure is 50 years and wires' residual strength cannot exceed 90 – 85% traditional way of defining heat resistance is not appropriate for estimation of long-term temperature of material work. With the regards above, practical problem that has been presented in the article lies in the elaboration of methodology and defining on its ground long-term heat resistance of selected aluminium alloys with addition of zirconium.

2. The problem

Studies on way of defining long-term heat resistance of aluminium and its alloys used for electric purposes for number of years [1-4]. In most of the works there have been analysed experimental results of studies on heat resistance and on this ground there have been built mathematical models mainly for excretory non-hardened aluminium alloys. The main aim of experimental studies and their analysis is elaboration of method of defining results of long-term temperature action on material tensile strength. Using for this purpose short-term (several hundred to several thousand h) temperature tests. Proposed methods in general do not include mechanism of structure renewal, often rely on typical mathematical methods of description and approximation of experimental studies results. From the material point of view the proper approach is using Arrhenius dependency, who proved that the speed of processes thermally activated (healing, recrystallization) can be expressed by exponential dependency [5]. On this ground logarithm diagram of speed of material properties changes in function of reciprocal temperature included in absolute scale is straight line, what allows extrapolation of results for long exposure time. Studies results of resistance of wires from aluminium on the grounds of Arrhenius diagram was presented in the work [6]. In document [7] there has been presented, on this ground, a new test having evaluation of heat resistance of wires from AlZr alloys in view. In the article, there has been used above method for defining heat resistance of AlZr alloys destined for production of conductors type HTLS (High Temperature Low Sag)

3. Research and discussion

3.1 Material for studies

Parametrization of heat resistance was conducted for three types of AlZr alloys (Table 1). Selection of zirconium content was made according to criteria of electrical conductivity [8]. The studies were conducted on wires with 3.5mm diameter obtained from wire rod with 9.5mm diameter. Mechanical and electrical properties of wires (Table 2) were in accordance to requirements of IEC [7].

Table 1. Chemical composition of studied alloys

Alloy	Fe	Si	Zr	Zn	Ti	V	Cr	Mn	Al
	(wt. %)								
AlZr0.021	0.159	0.051	0.021	0.002	0.002	0.006	0.001	0.002	rest
AlZr0.22	0.151	0.049	0.22	0.003	0.001	0.008	0.001	0.001	rest
AlZr0.26	0.197	0.061	0.26	0.007	0.002	0.001	0.001	0.003	rest

Table 2. Properties of wires from AlZr alloys

Alloy	YS (MPa)	UTS (MPa)	A_{250} (%)	ρ (nΩm)
AlZr0.021	174.6	196.0	1.4	28.78
AlZr0.22	153.7	166.9	2.4	28.73
AlZr0.26	157.0	174.2	2.3	28.71

3.2 Methodology and study results

First stage of studies was to assign standard dependencies of wire tensile strength in function of soaking heat in time of 1h (Fig. 1). Warming was conducted in a range of temperatures (140 to 500)^{o}C, every 10^{o}C. For selected wires from AlZr0.26 alloys fulfilling conditions of thermal treatment indicated by black arrow on Fig. 1 there were made metallographic observations (light microscope – Barker reagent; scanning microscope – BSE).

From the analysis of presented characteristics results that the character of course of softening curves of studied materials vary depending on alloy type. Beginning temperature of healing process is the same for studied alloys and is around 140^{o}C. In case of AlZr0.021 alloy, there has been observed characteristics refraction in temp 260^{o}C with about 20% of tensile strength decrease, and strength properties stabilisation on the lower level occur in temp. 360°C. Alloys with higher content of zirconium characterize with wider range of temperature in which healing process occurs (Fig. 1). For AlZr0.22 alloy this range is contains in section (140 – 430)°C, whereas for AlZr0.26 alloy - (140 – 450)°C. Decrease of tensile strength in both cases is about 30%. Temperatures of wire properties stabilisation on the lower level are 480°C and 500°C.

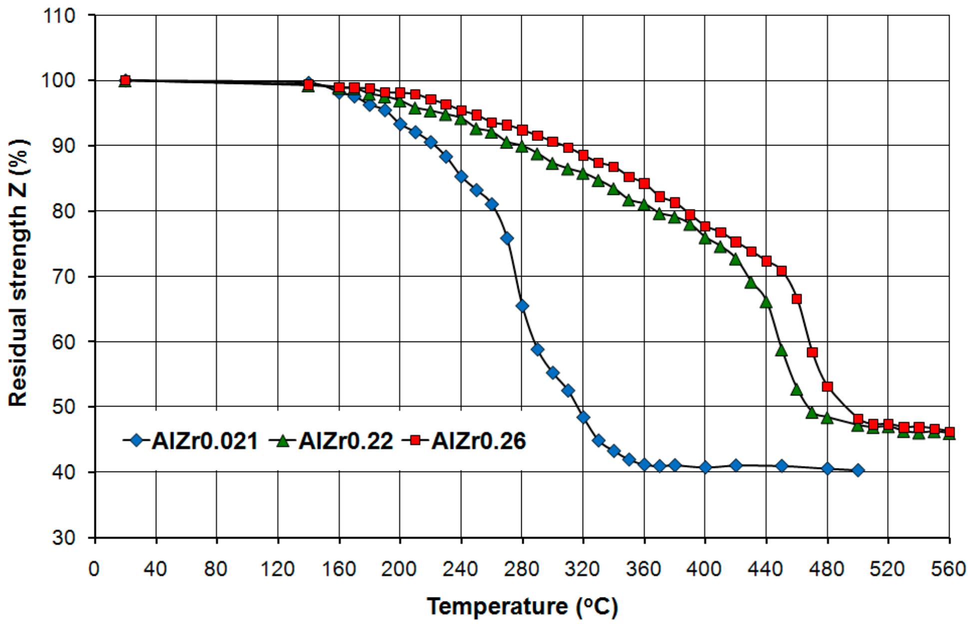

Fig. 1. Curves of softening of AlZr alloys

Observations of microstructure of wires from AlZr0.26 alloy in condition after drawing (Fig. 2a, 2b) indicate occurrence of typical subgrains elongated in the drawing direction.

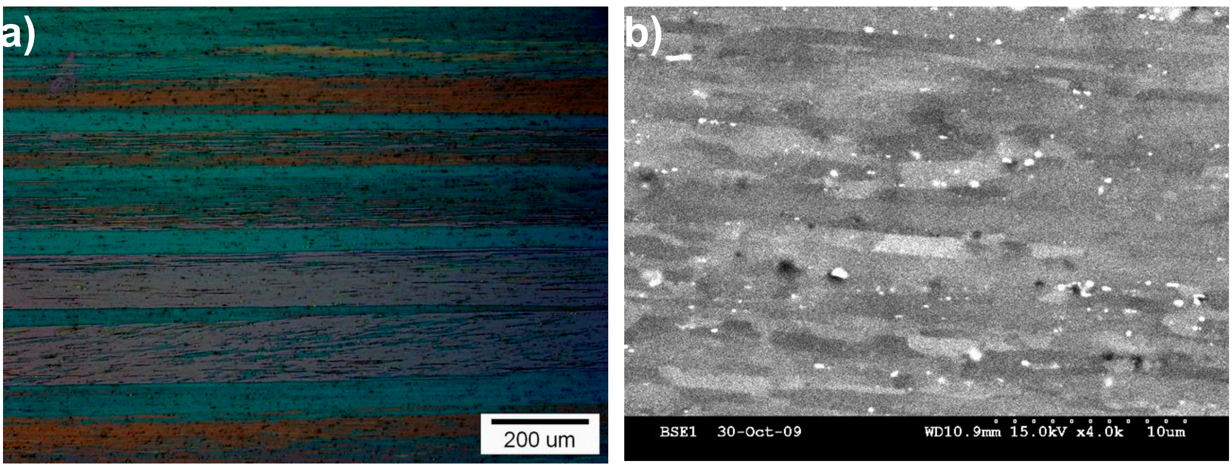

Fig. 2. Microstructure of AlZr0.26 wire after drawing: a) optical microscope, b) scanning microscope

In temperature 450°C there has been occurring in some material areas reconstruction of its structure, what expresses in developed line of limits and change of subgrains shape (Fig. 3A, 3b). In temperature 500°C material structure reaches stable equiaxial building what proves finishing of structure renewal process (recovery and recrystallization - Fig. 4A, 4b).

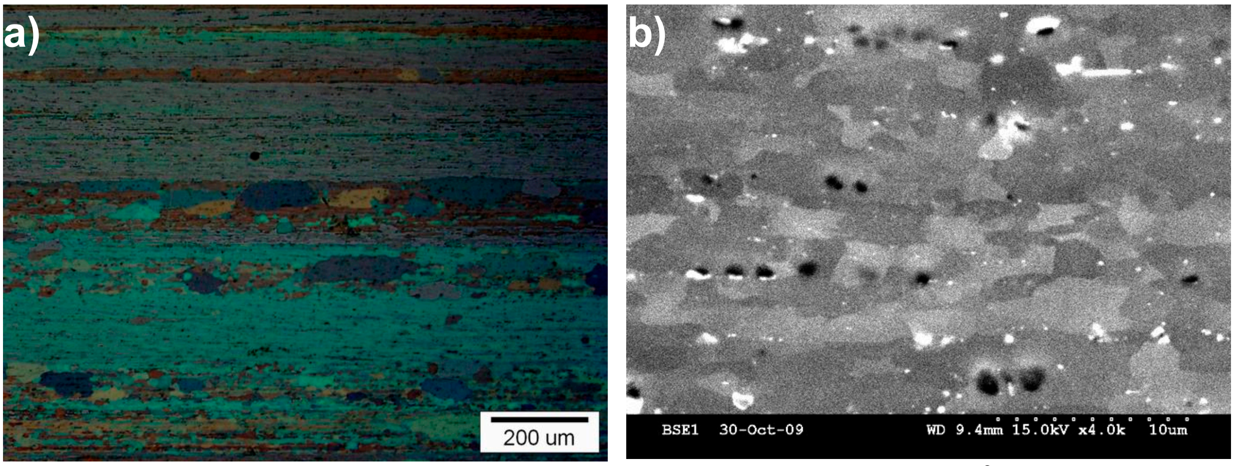

Fig. 3. Microstructure of AlZr0.26 wire after thermal treatment 450^{o}C/1h: a) optical microscope, b) scanning microscope

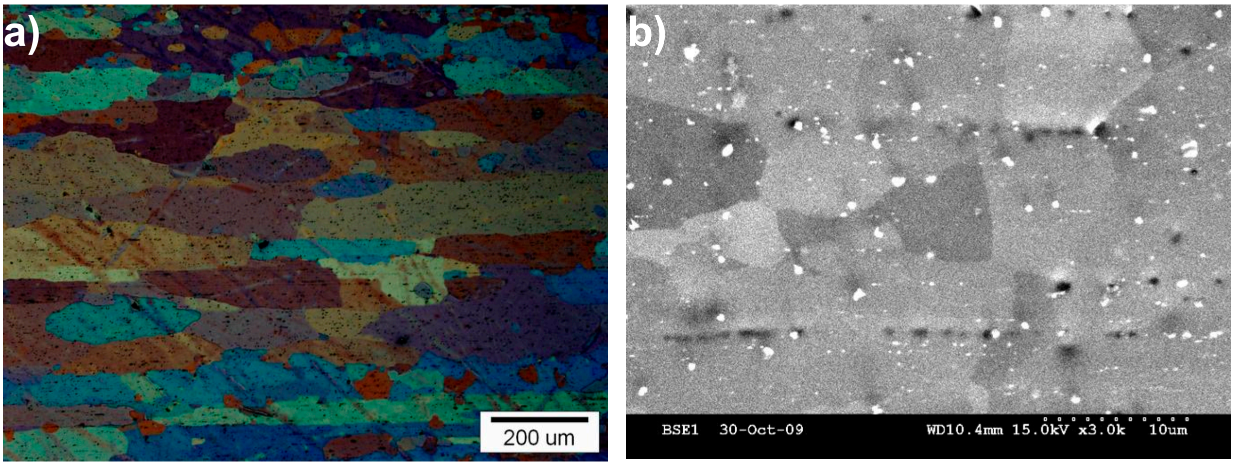

Fig. 4. Microstructure of AlZr0.26 wire after thermal treatment 500^{o}C/1h: a) optical microscope, b) scanning microscope

Obtained results allowed elaboration of program on second level of studies, that goal was quantitative definition of long-term heat resistance of studied alloys. For this purpose, there have been conducted tests of wire warming in selected (individually for each alloy) range of temperature every 5^{o}C in time to 1000h [6-7]. And so, for AlZr0.021 alloy the rage was (130 – 230)^{o}C, for AlZr0.22 alloy - (180 – 290)^{o}C, and for AlZr0.26 alloy - (210 – 300) ^{o}C. The basis of results analysis of heat resistance studies is Arrhenius equation in a form (1), describing speed of changes of processes thermally activated.

$$\frac{dZ}{dt} = Ae^{\frac{-Q}{RT}} \qquad (1)$$

dZ/dt is a speed of changes of tensile strength, when $Z = \frac{\Delta UTS}{UTS_I}$ is UTS_I initial value of strengthened material tensile strength, ΔUTS change of value tensile strength for material after thermal exposure, *A* is a constant value for given process conditions, *Q* is activation energy, and R is universal gas constant. Linearizationed form of equation (1) allows to define activation energy indispensable for obtaining specific decrease of tensile strength Z with defined level of material *ε* deformation.

$$\ln t = C + D\frac{1}{T} \tag{2}$$

Appearining in (2) constant data are expression of forms: $C = \ln\frac{Z}{A}$ and $D = \frac{Q}{R}$

Assuming constancy of degradation mechanisms of strength properties of material in assumed range of temperature and using equivalence principle of mechanical results of functioning influence of time and temperature appointed pairs set (t, T) corresponding to decrease of wire tensile strength to level 90% of initial strength. Such obtained data presented in lnt – 1/T configuration in a form of straight lines (points < 1000h) create Arrhenius plot (Fig. 5).

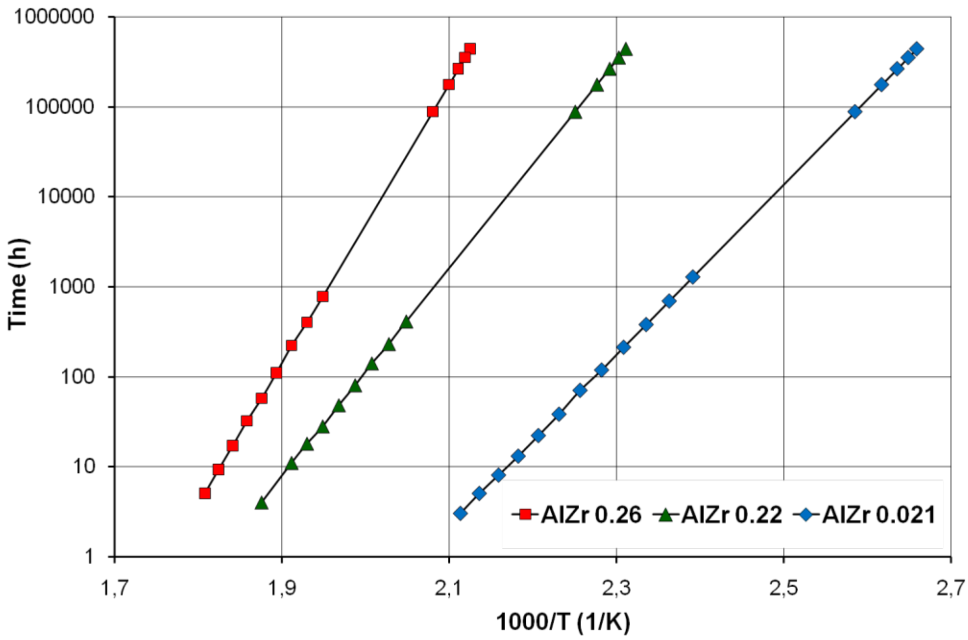

Fig. 5. Arrhenius plots of studied alloys (Z = 90%)

Extrapolation of experimental straight lines to assumed time of line exploitation e.g. 50 years (points >100000h) allows to estimate temperature value, in which there will be decrease of material tensile strength for 10% of initial value. Obtained in this way results of heat resistance of studied Al-Zr alloys for various holding time was placed in Table 3. In the table for comparison, there has been placed also results of aluminium heat resistance [4].

From the analysis of obtained data results that 50-years heat resistance of AlZr0,021 alloy is higher for about 20^{o}C. in relation to aluminium with assumed decrease of strength properties to the level of 90% of initial value. In relation to remaining alloys these temperatures are higher for 80^{o}C or 120^{o}C.

Table 3. Long-term heat resistance of AlZr alloys (wires with 3,5mm diameter)

Alloy	**Residual strength - 90%**			
	Time (years)			
	20	**30**	**40**	**50**
Al [4]	81	79	78	76
AlZr0.021	109	106	104	103
AlZr0.22	166	163	161	160
AlZr0.26	203	201	199	197

4. Conclusions

1. Addition of zirconium to aluminium increases long-term heat resistance of aluminium enabling in case of AlZr0.26 alloy increase of material work temperature to about 200^{o}C
2. Analysis of softening curves indicates that addition of zirconium to aluminium increases range of healing process occurrence.
3. Application of Arrhenius method enables by using short-term laboratory tests (to 1000h) indication of long-term heat resistance of the material.
4. Applied method of analysis of experimental studies results binds with assumption of constancy mechanisms of property degradation in examined temperature range, what is unambiguous with acceptance of equivalence principle of mechanical results of time and temperature activity.

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