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COMPARATIVE CHARACTERISTICS OF THE AlZr ALLOY MATERIALS ELECTRICAL AND MECHANICAL PROPERTIES

CHARAKTERYSTYKI PORÓWNAWCZE WŁASNOŚCI ELEKTRYCZNYCH I MECHANICZNYCH MATERIAŁÓW WYTWORZONYCH ZE STOPÓW AlZr

The subject of the present article consists in obtaining the wire production material with the controlled, during the heat treatment, level of electrical and mechanical properties. In the case of the AlZr alloys the appropriate strength properties are obtained in the technological process through the introduction of the specified value of the cold working (work-hardening). In turn,the AlZr alloy resistivity value is dependent on both the amount of the zircon additive and its placement characteristics in the aluminium structure (solid solution or emissions). The paper presents comparative resistivity and hardness tests of the AlZr alloy material with the zircon content ranging from 0.05 to 0.32% mas. Zr produced in the continuous casting technology as well as in the continuous casting and rolling technology.

Keywords: AlZr alloys, continuous casting aluminium alloys, electrical resistivity, wire rod, cast

Problematyka tematu artykułu, polega na uzyskaniu materiału do produkcji drutów o kontrolowanym, w procesie obróbki cieplnej poziomie własności elektrycznych i mechanicznych. W przypadku stopów AlZr uzyskanie odpowiednich własności wytrzymałościowych jest osiągane w procesie technologicznym poprzez wprowadzenie określonej wartości odkształcenia na zimno (umocnienie odkształceniowe). Z kolei wartość rezystywności stopu AlZr jest uzależniona zarówno od ilości dodatku cyrkonu jak i charakteru jego ulokowania w strukturze aluminium (roztwór stały lub wydzielenia). W pracy przedstawiono badania porównawcze rezystywności i twardości, materiału ze stopów AlZr, o zawartości cyrkonu w zakresie od 0,05 do 0,32% mas. Zr, wytworzonego w technologii ciągłego odlewania oraz w technologii ciągłego odlewania i walcowania.

1. Introduction

Production of the continuously cast materials is performed with the use of two kinds of technologies: high-capacity production lines i.e. continuous casting and hot rolling lines (CCR), and lower-capacity technologies for special purposes i.e. continuous casting lines (CC). Table 1 presents selected examples of the aluminium and aluminium alloy continuous casting technologies.

Considering aluminium and aluminium alloy production technologies, particular attention should be paid to the process parameters which allow to obtain finished products in the form of a casting bar or wire rod i.e. cold-deformed or hot-deformed materials. Table 2 contains a fragmentary comparison of the hot and cold deformation process parameters

TABLE 1
Continuous casting technologies used for aluminum [1, 2]

Cast product	Technology	Cast material
Rod, Bar and Wire	Properzi Process for Continuously Cast and Rolled Rod	Al, Pb, Zn, Cu
	Cegedur- Pechiney- Secim Continuous Casting and Rolling Process	Al
	Southwire Aluminium SCR Systems	Al, Cu
Ingot, Slab and Billet	Clark Single-Strand Horizontal-Casting System	Al
	Magstaff Horizontal-Casting Machine	Al
	Reynolds Horizontal-Casting Process	Al
	Kaiser Aluminium Process for Horizontal Continuous Casting	Al
	Alcoa Horizontal Continuous-Casting Process	Al

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TABLE 2

Hot and cold deformation parameters statement [3]

	Hot deformation	**Cold deformation**
1. Objectives	a. Large change in dimensions b. Replace cast structure with more uniform one	Precise final dimensions Produce selected final structure and properties
2. Operations	Preheating-deformation-cooling Multistage: many stages or passes without reheating	Deformation with or without final annealing Multistage usually with occasional intermediate annealing
3. Equipment	a. Large scale because of 1a	Strong because of 5a, b
	b. Rough tooling Tooling wear high-rough oxidized surface of high T workpiece	Smooth, precise tooling
		Tooling fatigue life short-high stresses
	c. Lubrication poor (also coolant)	Lubrication good
	Friction high	Friction low
4. Starting stock	Cast material, large dimensions	HW or CW + annealed, small
	Surface rough, conditioned to cut-out defects, possibly scarfed	HW pickled micro-rough CW + anneal clean smooth
	Microstructure	Equiaxed fine grains, homogeneous stringers or preferred crystal orientation
	Large columnar grains, segregation inside and between grains, large inclusions, blowholes, weak surface	Directional properties due to fibrous stringers or preferred crystal orientation
5. Forces and work	Yield stress low	High due to internal structure and mechanisms – increases indefinitely
	Maximum flow stress internal structure and mechanisms static recovery, work hardening rate low, increases as ↑ decreases as T↑, friction high	High strain hardening rate almost independent of ↑ small decrease with T, friction low
	Force: low due to 5a, b	
	Work: up due to large areas 3a Up due to 1a, 3b, 6	High due to 5a, b Down due to small contact areas
	For soft product	
	Thermal: high	Mechanical: high
	Mechanical electrical/E: low	Thermal: high for annealing
	For hard product	
	Quenching: low	Thermal: low no anneal
	If heat treatment: high	
6. Ductility	High in limited range of T and (usually ↓ as T↓, ↑)	Low unaffected by (<10^3 s^{-1})
	T must be less than TM even heat of working – incipient melting, burning at GB-hot short	Useful increase as T raised, limited by need to avoid oxidation or breakdown of lubricant
	High reductions common	Usually small reductions

In the industrial conditions the AlZr alloys are produced mainly in the continuous casting and hot rolling process (CCR) Continuus Properzi. Generally speaking, the CCR process may be divided into three basic stages: metallurgical i.e. all the activities performed to prepare the ingot, its melting, alloying, and casting on the Properzi casting wheel. Secondly, the hot deformation is performed in a rolling mill of 13 stands operating in the triangle-circle system. The following stage is the heat treatment stage of the wire rod with the diameter of 9.5 mm. By choosing such parameters as casting speed, control of the casting wheel and the particular rolling mill stands cooling intensity, the obtained wire rod has high strength properties amounting to from 140 to 160 MP, and its resistivity amounting to approximately 32 nΩm. Such level of properties points to the alloy oversaturation taking place on the casting wheel on one hand, and to the material recovery during the rolling process on the other. In order to lower the electrical properties of the wire rod it is subject to heating in the temperature ranging from 360-420°C in the time up to 120 h [4].

One of the conceptions in the papers on the aluminium and aluminium alloy wire manufacturing technologies consists in the omission of the hot deformation segment and, simultaneously, eliminating additional heat treatment. This method, due to the recovery process of the aluminium subject to hot deformation in the CCR lines, eliminates the necessity to anneal the wire rod into the annealed condition, which significantly lowers production costs of such material. Such technology assumes continuous casting of the aluminium rod of the desired diameter, and, subsequently, its direct drawing to form wires for twisting or the ingot for other technological processes. The basic advantage of the continuous casting technology (CC) is the lower investment outlay as compared with the CCR system. Moreover, it's characteristic feature is versatility of the produced diameters and the size of installations, however, a negative aspect of the CC technology, as compared with the CCR line, may be its low efficiency. The enumerated factors contribute to the fact that the aluminium and aluminium alloy ingot production is interesting mainly for small cable manufacturing establishments which may produce the ingot for drawing for their own needs [5, 6, 7].

The choice of the casting conditions such as the liquid metal temperature or crystallization speed is made with the use of the AlZr alloy dual balance system, and more specifically, with the use of the liquidus line trajectory, while the trajectory of the solidus line allows to determine the optimum alloy heat treatment temperature on the basis of the determination of the obtained material's resistivity. Following the papers by Belov and Toporov, the main factors contributing to the possibility of the aluminium solution oversaturation with zircon should include the casting temperature, crystallization speed, and Al_3Zr phase primary precipitations present in the liquid. The crystallization speed should exceed 5 K/s, while the casting temperature should exceed the liquidus line temperature by approximately 40-50°C (according to Belov) [8, 9].

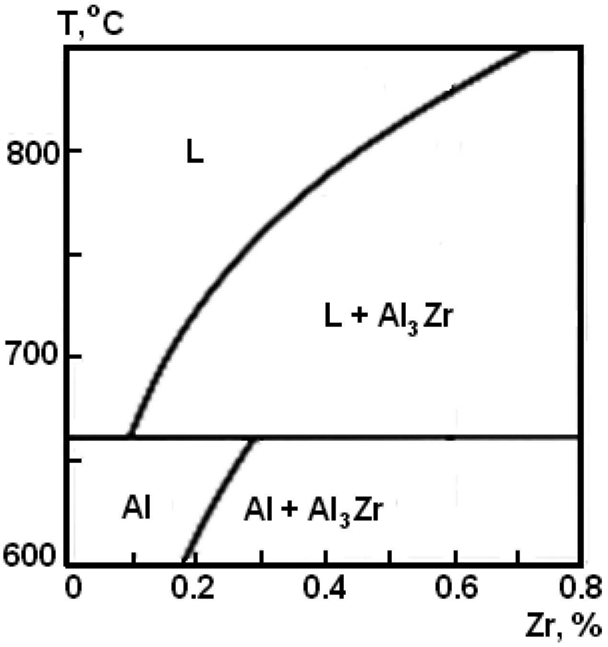

Fig. 1. An extract from the AlZr alloy dual balance system [10]

The peculiarity of the AlZr alloy casting consists in the fact that the entire zircon should enter the solid solution of aluminium. Therefore, such alloys require higher melting and casting temperature, which can be read from the AlZr phase diagram, which is characterized by the considerable growth of the liquidus temperature accompanied by the increase of the concentration of zircon. Later, during the heat treatment, zircon should entirely precipitate from the solid solution of aluminium. In the form of the Al_3Zr phase responsible for the structure and reinforcement.

The tested material

The tests were performed on the material from the continuous casting and rolling line in the form of an ingot with the surface of 2065 mm^2 obtained from a Properzi casting wheel and a wire rod with the diameter of 9.5 mm obtained from the CCR line. Table 3 presents the general chemical composition of the tested materials.

TABLE 3

The chemical composition of the tested AlZr alloys, mas.%

Al	Zr	Fe	Si
99.70	0.05	0.146	0.058
99.65	0.09	0.156	0.063
99.60	0.15	0.133	0.063
99.45	0.22	0.185	0.067
99.40	0.29	0.163	0.070
99.42	0.32	0.122	0.067

The materials were subject to the heat treatment in the temperature range from 100°C to 620°C for 192 hours every 24 hours (the article presents only selected heat treatment time spans i.e. 24 h, 120 h, and 192 h. The ingots and the wire rod were subject to the resistivity test (Sigmatest Foerster Company) and the Brinell hardness test.

Test results and their analysis

On the basis of the performed tests the following results concerning the changes of resistivity and Brinell hardness in temperature have been obtained. The resistivity results are presented for the ingots in Fig. 2, 4, 6, 8, 10, 12, for the wire rod in Fig. 3, 5, 7, 9, 11, 13.

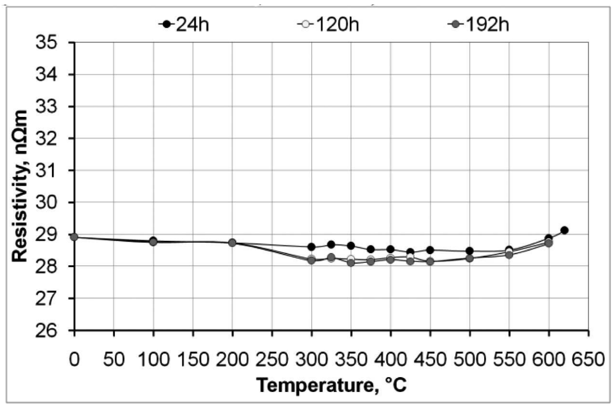

Fig. 2. Statement of resistivity change with temperature for the Al0,05Zr alloy (the ingot)

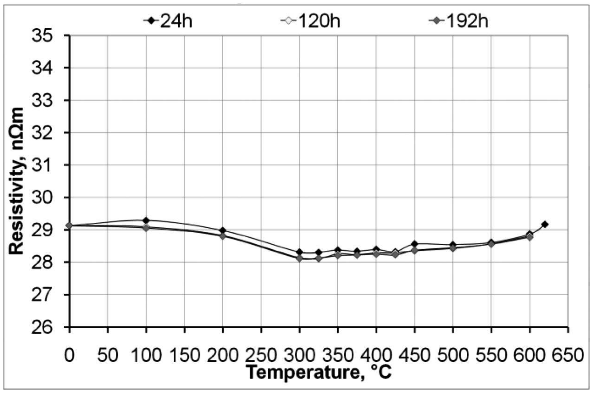

Fig. 3. Statement of resistivity change with temperature for the Al0,05Zr alloy (the wire rod)

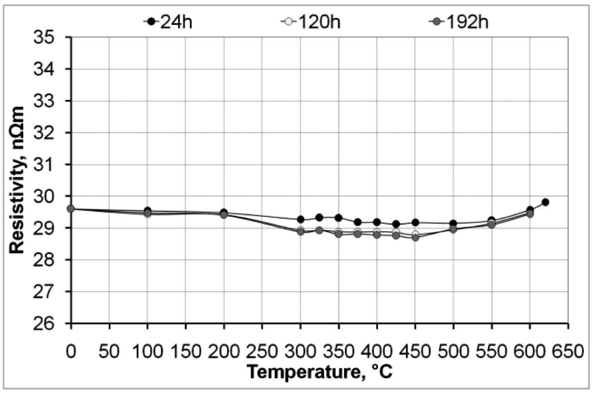

Fig. 4. Statement of resistivity change with temperature for the Al0,09Zr alloy (the ingot)

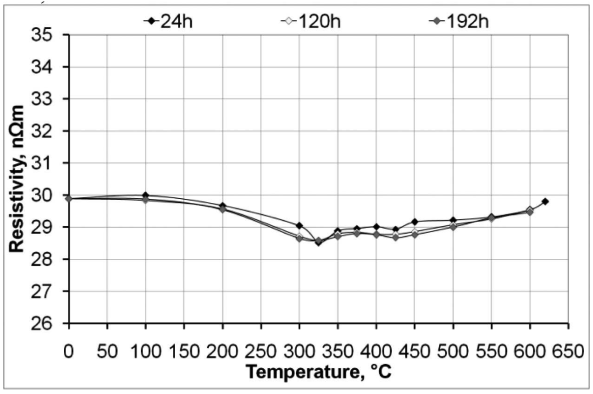

Fig. 5. Statement of resistivity change with temperature for the Al0,09Zr alloy (the wire rod)

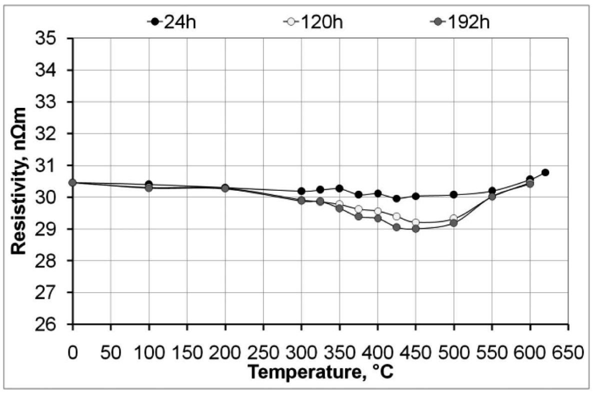

Fig. 6. Statement of resistivity change with temperature for the Al0,15Zr alloy (the ingot)

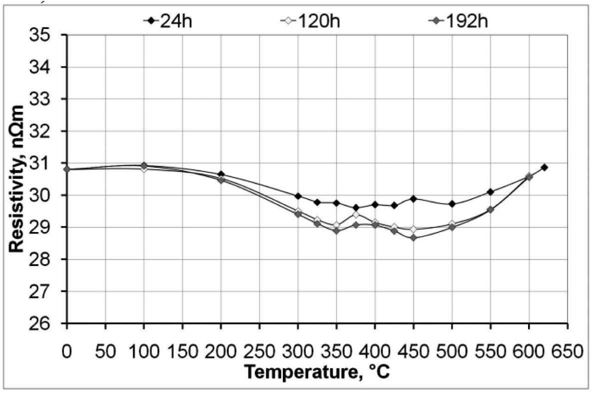

Fig. 7. Statement of resistivity change with temperature for the Al0,15Zr alloy (the wire rod)

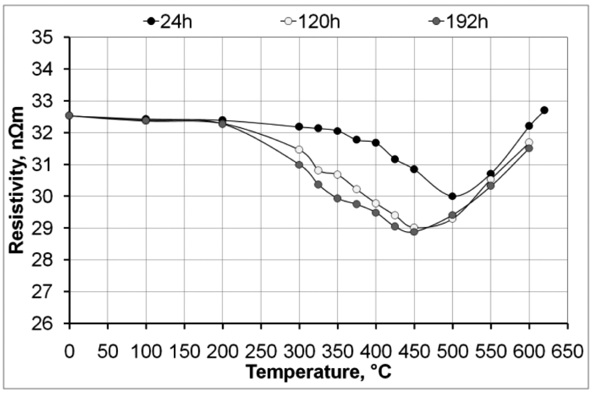

Fig. 8. Statement of resistivity change with temperature for the Al0,22Zr alloy (the ingot)

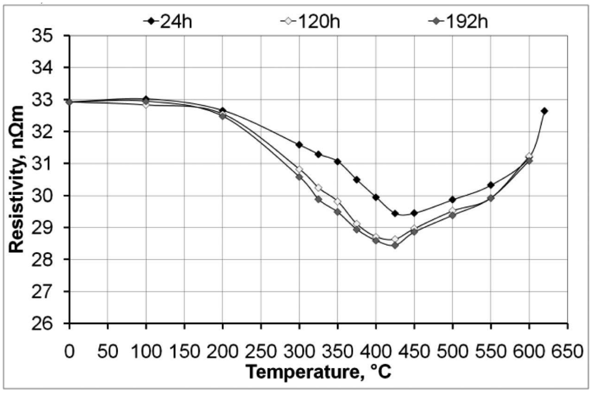

Fig. 9. Statement of resistivity change with temperature for the Al0,22Zr alloy (the wire rod)

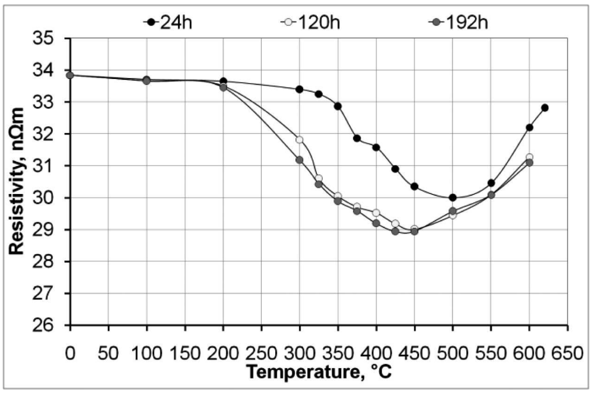

Fig. 10. Statement of resistivity change with temperature for the Al0,29Zr alloy (the ingot)

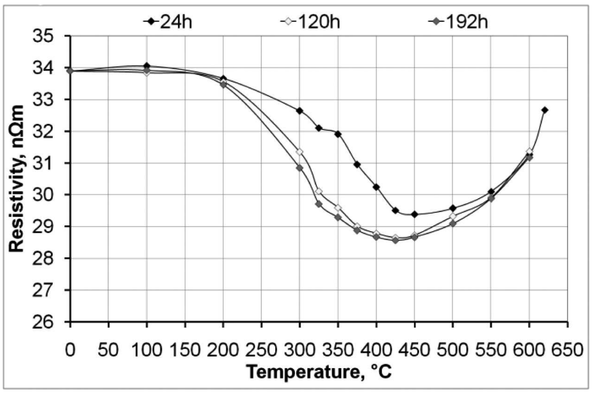

Fig. 11. Statement of resistivity change with temperature for the Al0,29Zr alloy (the wire rod)

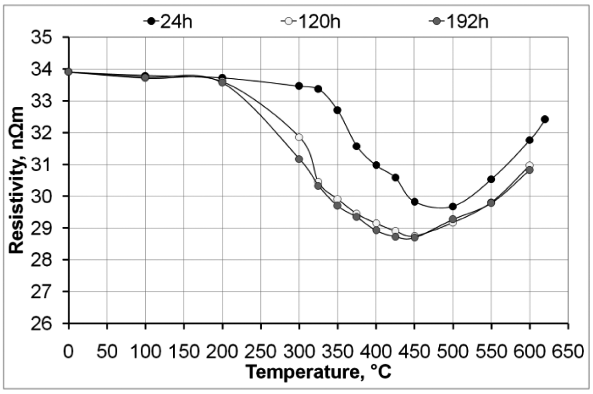

Fig. 12. Statement of resistivity change with temperature for the Al0,32Zr alloy (the ingot)

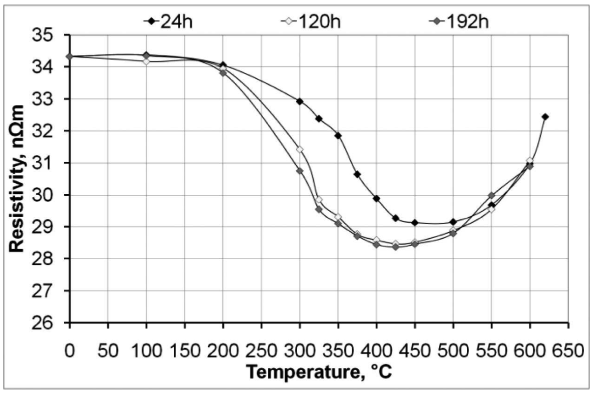

Fig. 13. Statement of resistivity change with temperature for the Al0,32Zr alloy (the wire rod)

The difference in the obtained resistivity results for the AlZr0,05 alloy (Fig. 2, Fig. 3) and for the AlZr0,09 alloy (Fig. 4, 5) is contained between 28 and 30 nΩm both for the ingot and the wire rod. The above resistivity changes allow to determine the optimum heat treatment parameters i.e. the temperature of 350°C and the time of 192 hours for the AlZr0,05 alloy. The lowest resistivity for the AlZr0,09 is obtained in the temperature of 450°C and the time of 192 hours. The resistivity curves for the AlZr0,05 alloy Fig. 6 and 7 have the U shape, most probably resulting from the gradually decreasing amount of the precipitated zircon from the aluminium solution in temperature. In this case, the most beneficial heat treatment conditions for the ingot is the temperature of 450°C and the time of 192 hours, while for the wire rod – the temperature of 425°C and the time of 192 hours. The characteristics of the resistivity changes for the AlZr0,22, AlZr0,29, and AlZr0,32 presented respectively for the ingot in Fig. 8, 10, and 11, while for the wire rod in Fig. 9, 11, and 13 show a clearly marked shape of the letter U. The shape of the resistivity change in temperature graphs is connected with the course of the zircon precipitation process from the aluminium solution. The obtained lowest resistivity values for the ingot at the heating time of 192 hours and the temperature of 450°C, and for the wire rod for the time of 192 hours and the temperature of 425°C divide the graphs into two parts to the temperature of 425 and 450°C the heat-activated diffusion processes, which lead to the gradual decrease of resistivity, take place, while above the mentioned temperatures the balanced conditions are approached.

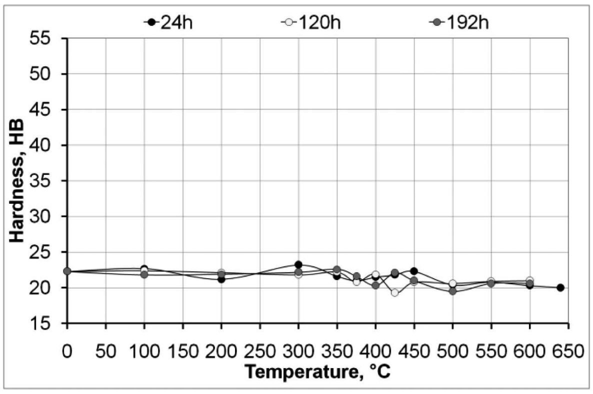

Fig. 14. Statement of hardness change with temperature for the Al0,05Zr alloy (the ingot)

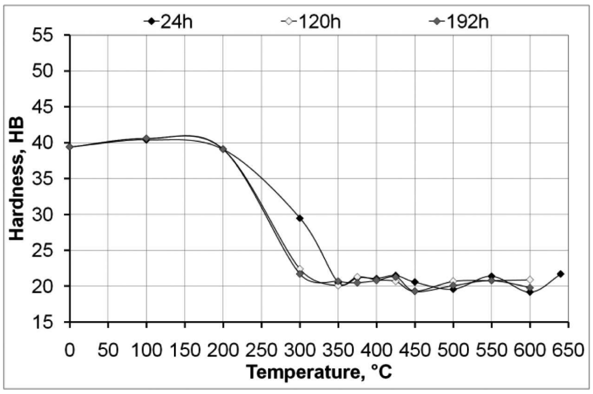

Fig. 15. Statement of hardness change with temperature for the Al0,05Zr alloy (the wire rod)

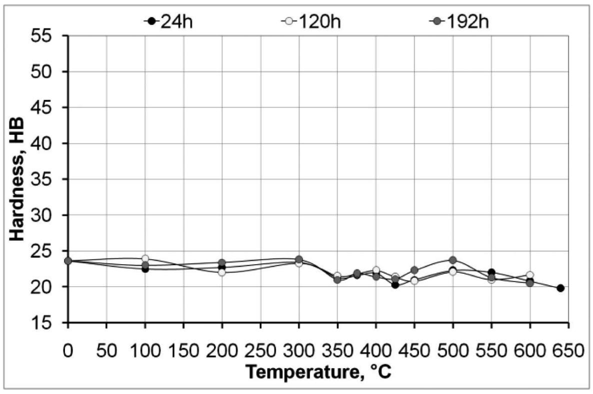

Fig. 16. Statement of hardness change with temperature for the Al0,09Zr alloy (the ingot)

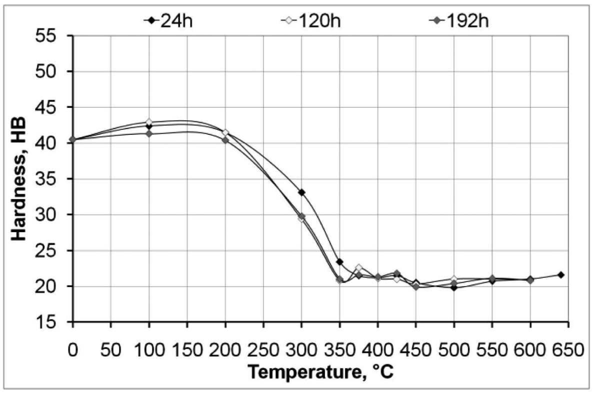

Fig. 17. Statement of hardness change with temperature for the Al0,09Zr alloy (the wire rod)

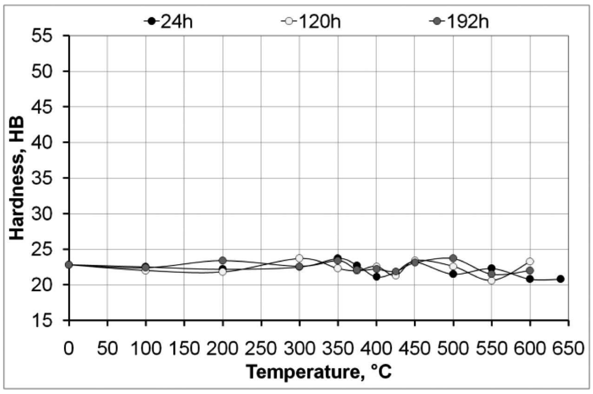

Fig. 18. Statement of hardness change with temperature for the Al0,15Zr alloy (the ingot)

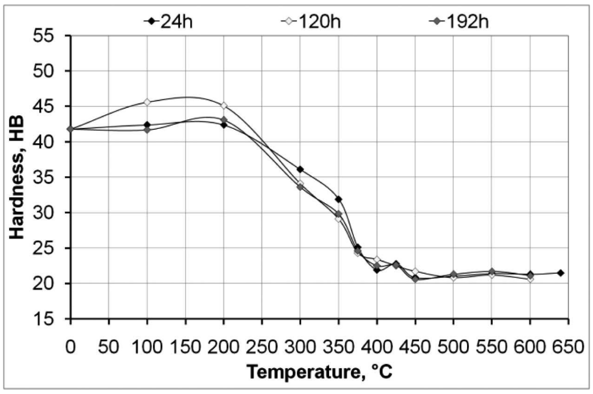

Fig. 19. Statement of hardness change with temperature for the Al0,15Zr alloy (the wire rod)

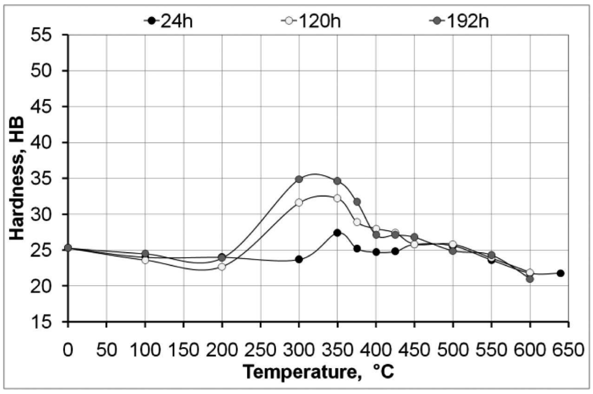

Fig. 20. Statement of hardness change with temperature for the Al0,22Zr alloy (the ingot)

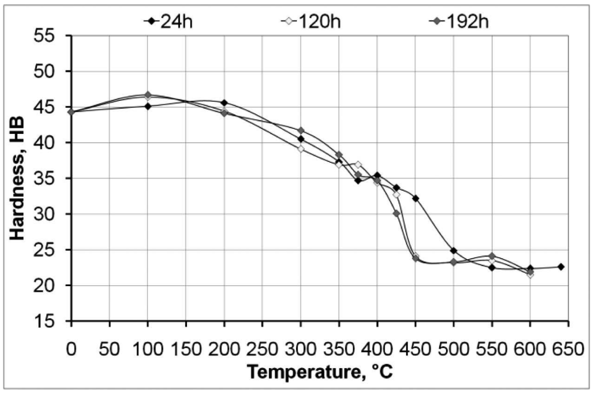

Fig. 21. Statement of hardness change with temperature for the Al0,22Zr alloy (the wire rod)

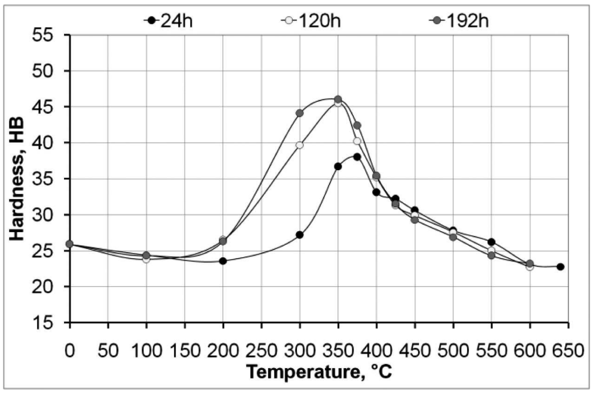

Fig. 22. Statement of hardness change with temperature for the Al0,29Zr alloy (the ingot)

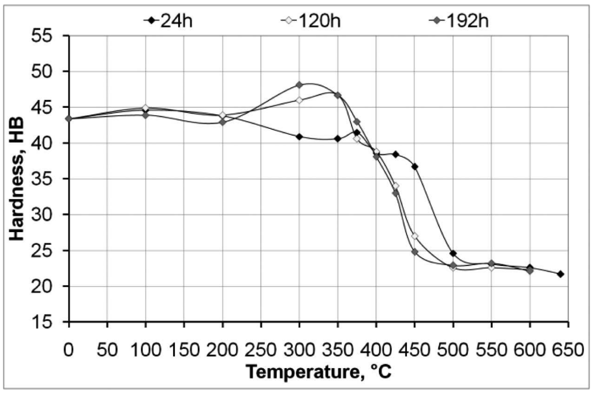

Fig. 23. Statement of hardness change with temperature for the Al0,29Zr alloy (the wire rod)

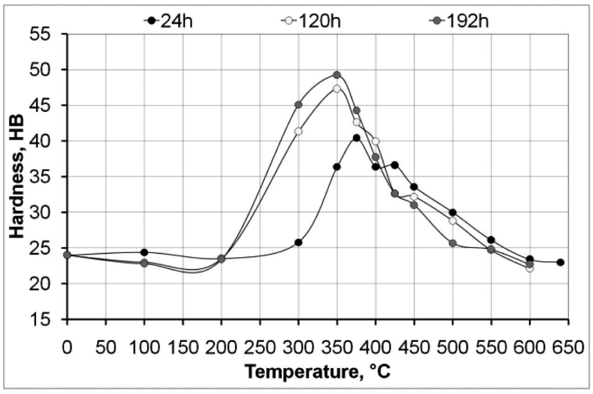

Fig. 24. Statement of hardness change with temperature for the Al0,32Zr alloy (the ingot)

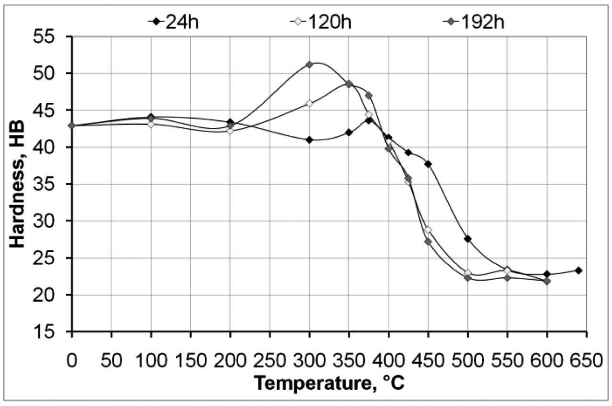

Fig. 25. Statement of hardness change with temperature for the Al0,32Zr alloy (the wire rod)

In the analyzed conditions of the heat treatment process the tested hardness of the alloy in the post-casting condition for the AlZr0,05, AlZr0,09, and AlZr0,15 alloys Fig. 14, Fig. 16, Fig. 18, so in the soft condition, does not show clear signs of the precipitation hardening process. The hardness ranks between 25 and 30 HB. The hardness test results for the AlZr0,22 alloy (Fig. 20) are characterized by the presence of the precipitation hardening process of the alloy. From this point of view, the most beneficial appears to be the temperature of 350°C and the time of 192 hours, for which the initial hardness value of 25 HB increases to the value of 35 HB. In the case of the mechanical properties of the AlZr0,29 and AlZr0,32 alloys (Fig. 22 and Fig. 23) the maximum on the aging curve is obtained for the temperature of 350°C, aproximately 46 HB and nearly 50 HB respectively. In the case of the wire rod hardness, in the tested temperature range, it can be observed that the highest hardness value for the AlZr0,05 (Fig. 15), AlZr0,09 (Fig. 17), AlZr0,15 (Fig. 19), and AlZr0,22 (Fig. 21) alloys has been obtained for the temperatures up to 200°C in the range from 40 to 50 HB. The recrystallization temperature of the AlZr0,05 and AlZr0,09 alloys amounts to 350°C, while for the AlZr0,15 it increases to the value of 400°C, hence by 50°C as compared to the materials with lower content of zircon (0.05, 0.09). For the AlZr0,22 alloy the recrystallization temperature is 450°C. The course of hardness change for the AlZr0,29 (Fig. 23) and AlZr0,32 (Fig. 25) alloys, the hardness increase between 300 and 350°C can be noted, resulting most probably from the precipitation hardening process of the alloy during heating.

Conclusions

On the basis of the performed research the following conclusions have been drawn:

1. The character of the resistivity change of the tested materials is due to the variable solubility limit of the alloy, which causes that in the high temperatures of the heat treatment process a small amount of zircon precipitates, which relates to the high resistivity of the alloy.
2. The applied heat treatment of the cast material with the content of zircon above 0.15 permits precipitation hardening. In the case of hot-deformed material of this kind the situation occurs only for the alloy with the 0.29% zircon content.
3. Heat treatment of the hot-deformed AlZr alloys allows to improve the diffusion conditions of zircon which is represented in the resistivity change characteristics of the tested materials.

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