COMPARATIVE CHARACTERISTICS OF THE AlZr ALLOY MATERIALS ELECTRICAL AND MECHANICAL PROPERTIES

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

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.

| Cast product | Technology | Cast material |
|--------------|------------|---------------|
| Rod, Bar and Wire | Properzi Process for Continuously Cast and Rolled Rod | Al, Pb, Zn, Cu |
| | Cegedor- 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 |
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

| TABLE 2: Hot and cold deformation parameters statement [3] |
|-----------------------------------------------|
| **1. Objectives** | **Cold deformation** |
| a. Large change in dimensions | Precise final dimensions |
| b. Replace cast structure with more uniform one | Produce selected final structure and properties |
| **2. Operations** | **Cold deformation** |
| Preheating-deformation-cooling | Deformation with or without final annealing |
| Multistage: many stages or passes without reheating | Multistage usually with occasional intermediate annealing |
| a. Large scale because of 1a | Strong because of 5a, b |
| b. Rough tooling | Smooth, precise tooling |
| Tooling wear high-rough oxidized surface of high T workpiece | Tooling fatigue life short-high stresses |
| c. Lubrication poor (also coolant) | Lubrication good |
| Friction high | Friction low |
| **3. Equipment** | **Cold deformation** |
| 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 |
| **4. Starting stock** | **Cold deformation** |
| 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 | High due to 5a, b Down due to small contact areas |
| Work: up due to large areas 3a Up due to 1a, 3b, 6 | For soft product |
| For hard product | Thermal: high |
| Quenching: low | Mechanical: high |
| If heat treatment: high | Thermal: high for annealing |
| **5. Forces and work** | **Cold deformation** |
| High in limited range of T and (usually ↓ as T↑, ↑) | Low unaffected by (<10⁷ 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

| TABLE 2: Hot and cold deformation parameters statement [3] |
|-----------------------------------------------|
| **1. Objectives** | **Cold deformation** |
| a. Large change in dimensions | Precise final dimensions |
| b. Replace cast structure with more uniform one | Produce selected final structure and properties |
| **2. Operations** | **Cold deformation** |
| Preheating-deformation-cooling | Deformation with or without final annealing |
| Multistage: many stages or passes without reheating | Multistage usually with occasional intermediate annealing |
| a. Large scale because of 1a | Strong because of 5a, b |
| b. Rough tooling | Smooth, precise tooling |
| Tooling wear high-rough oxidized surface of high T workpiece | Tooling fatigue life short-high stresses |
| c. Lubrication poor (also coolant) | Lubrication good |
| Friction high | Friction low |
| **3. Equipment** | **Cold deformation** |
| 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 |
| **4. Starting stock** | **Cold deformation** |
| 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 | High due to 5a, b Down due to small contact areas |
| Work: up due to large areas 3a Up due to 1a, 3b, 6 | For soft product |
| For hard product | Thermal: high |
| Quenching: low | Mechanical: high |
| If heat treatment: high | Thermal: high for annealing |
| **5. Forces and work** | **Cold deformation** |
| High in limited range of T and (usually ↓ as T↑, ↑) | Low unaffected by (<10⁷ 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 |
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$_3$Zr 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].

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.

### 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.

| 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 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.

### 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. 1. An extract from the AlZr alloy dual balance system [10]](image)

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$_3$Zr phase responsible for the structure and reinforcement.

![Fig. 2. Statement of resistivity change with temperature for the Al0.05Zr alloy (the ingot)](image)
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)
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 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 temperature of 425°C and 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. 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)
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, approximately 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.

Acknowledgements

The research was performed within the AGH contract no 15.11.180.656.

REFERENCES

[1] H.D. Merchant, D.E. Tyler, E.H. Chia, Continuous Casting of Non-Ferrous Metals and Alloys. TMS 1989.

[2] C. Kamm er, Continuous casting of aluminium. Supplement 3, TALAT Lecture 3210.

[3] H.J. McQueen, S. Spigarelli, M.E. Kassner, E. Evangelista, Hot Deformation and Processing of Aluminum Alloys, Manufacturing Engineering and Materials Processing, CRC Press; 1 edition (September 28, 2011).

[4] T. Knych, M. P iowski ska, P. Uliasz, Studies on the process of heat treatment of conductive AlZr alloys obtained in various productive processes Archives of Metallurgy and Materials 56, 3, 685-692 (2011).

[5] T. Knych, P. Kwasi niewski, G. Kiesiewicz, M. P iowski ska, P. Uliasz, Study about drawing aluminium rod made by continuous casting. Rudy i Metale Niezelazne 55, 7, 464-469 (2010).

[6] T. Knych, P. Uliasz, M. P iowski ska, Research on technology for continuous casting rods with aluminium for direct drawing. Materials of Krakow Conference Young of Scientists ProFuturo, Kraków (2010), p. 31-41.

[7] T. Knych, P. Uliasz, M. P iowski ska, Badania nad nową technologią wytwarzania wsadu do produkcji drutów aluminiowych. Wiadomości Hutnicze Hutnik

[8] V.S. Zolotorevsky, N.A. Belov, Casting aluminium alloys, Elsevier, 2007.

[9] L.S. Toropova, D.G. Eskin, M.L. Kharakterova, T.V. Dobatkina, Advanced Aluminium Alloys Containing Scandium: Structure and Properties, Taylor & Francis, 1998.

[10] Н.А. Белова, А.Н. А лабина, А.И. П роко ров, Влияние отката на сопротивление и механические свойства литых сплавов холодной Al-0,6% (масс.) Zr, Цветы Металлы, 10, 65-68 (2009).

Received: 10 September 2013.