

## STRUCTURE AND TENSILE PROPERTIES OF Pb–0.3%Sn–0.1%Ca NEGATIVE GRID ALLOY FOR LEAD-ACID BATTERIES

✉ Victor O. Dzenzerskiy, ✉ Serhii V. Tarasov, ✉ Olena V. Sukhova\*, ✉ Dmytro O. Redchys, ✉ Volodymyr A. Ivanov

*Institute of Transport Systems and Technologies of National Academy of Sciences of Ukraine  
5, Pisarzhevsky St., Dnipro, 49005, Ukraine*

\*Corresponding Author e-mail: [sukhovaya@ukr.net](mailto:sukhovaya@ukr.net)

Received January 16, 2025; revised April 14, 2025; accepted May 12, 2025

The structure and tensile properties of Pb–0.3%Sn–0.1%Ca alloy for negative grids of lead-acid batteries have been characterised as functions of mould preheating temperature during casting and ageing time during storage under atmospheric conditions. Several techniques have been used to study microstructure, including quantitative metallography, scanning electron microscopy, and energy dispersive analysis. Tensile properties such as ultimate tensile strength, yield strength, Young's modulus, and elongation have been determined at room temperature. The increase of mould preheating temperature in the range between 60 °C and 170 °C causes the decrease in ultimate tensile strength (by ~25 %) and increase in elongation (by ~50 %) due to twofold increase in the grain size of the alloy. Whereas natural ageing for 35 days influences neither grain size nor tensile properties markedly.

**Keywords:** Lead-acid batteries; Negative grids; Lead-tin-calcium alloy; Casting conditions; Mould temperature; Natural ageing; Grain size; Tensile properties

**PACS:** 61.82.Bg, 61.66.Dk, 62.20.-x, 62.20.Fe, 62.20.Mk, 64.70.Dv, 81.70.Bt, 81.40.Cd, 81.40.Lm

Over the last years, there has been substantial interest in lead-acid batteries which require no further maintenance throughout the expected life of the battery [1,2]. This type of maintenance-free batteries is currently in widespread use [3,4]. A considerable amount of attention over the years has been given to the type of alloys used for manufacturing negative grids in such maintenance-free batteries [5,6]. Much interest has centered around the use of lead-tin-calcium alloys for making such grids [7-9].

The properties of lead-tin-calcium alloys depend mainly on the ratio of tin-to-calcium content (Sn/Ca) [10,11]. Often, the materials of choice for the negative grids have been alloys with low tin-to-calcium ratios (Sn/Ca<9) [12,13]. The calcium content in such alloys has been at least about 0.1 % by weight while the tin has generally been at about 0.3 % [14,15]. These ternary alloys are classic precipitation-strengthening alloys which derive mechanical strength due to a dispersion of very fine intermetallic precipitates in a lead-based matrix [16-19]. For lead-tin-calcium alloys with ratios below 9, the strengthening process is similar to that of lead-calcium alloys [20,21]. Strengthening occurs very rapidly with the formation of stable Pb<sub>3</sub>Ca precipitates [22,23]. But due to tin additives to the binary Pb–Ca alloys the mode of precipitation changes from Pb<sub>3</sub>Ca to more stable and stronger (Pb,Sn)<sub>3</sub>Ca precipitates [24,25].

The service life requirements for negative grid alloys are diverse [26,27]. Service conditions heighten the importance of grid strength to avoid premature failure of performance. Accordingly, enhancing the structure and tensile properties stability of the negative grids is an important demand. Excessive negative grid dimensional changes can result in premature failure in service and thus must be carefully controlled.

Production equipment to fabricate negative grids is now commercially available by which battery grids can be made by a variety of casting technologies [12]. Potentially, the use of any casting process to make negative grids is capable of minimizing problems associated with structural and dimensional stability. Several methods can be used at the casting step to control the microstructure of negative grid alloys. Most of these methods operate by exercising strict control of cooling rate from the melt [28-30]. For example, simple changes in such parameter as mould preheating temperature have been commonly used over the years to control grain size and precipitated phase dispersion [31,32].

Thus, proven methods to increase tensile properties required in negative grid alloys for efficient processing are to control casting procedure and monitor ageing processes. However, the tensile properties of the negative grids, which are among important factors limiting the life of the lead-acid battery, have not been intensively investigated. Over the last 30 years a vast range of research has been focused on the additives into lead-tin-calcium alloys, strengthening mechanisms, hardness and/or resistivity measurements etc. Therefore, the aim of this work is to investigate effects of mould preheating temperature during casting and ageing time during storage under atmospheric conditions on such mechanical properties as ultimate tensile strength, yield strength, elongation, and Young's modulus of Pb–0.3%Sn–0.1%Ca negative grid alloy.

## MATERIALS AND METHODS

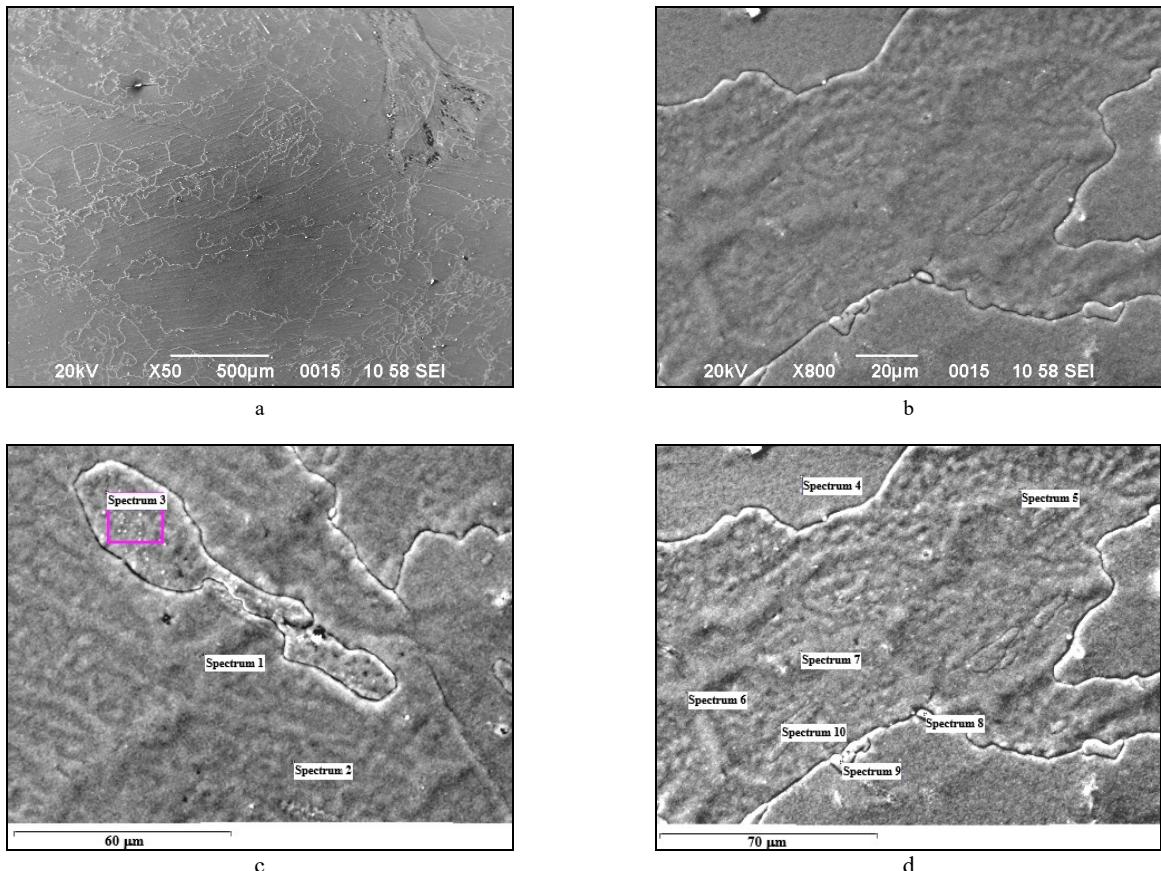
The Pb–0.3%Sn–0.1%Ca (in wt. %) grid alloy was commercially produced in the C.O.S. melting pot of production line for negative grids of lead-acid batteries of *BM* Company (Austria) at *Westa* Corp. (City of Dnipro, Ukraine). Molten metal at the temperature of  $465 \pm 5$  °C was poured into a casting mould preheated in the range between 60 °C and 170 °C to prepare specimens for the tensile tests. The temperature was measured by chromel-alumel thermocouple and temperature variation during casting did not exceed  $\pm 3$  °C. Chemical composition of the alloy was determined using an ARL 3460 optical emission spectrometer. Trace amounts of major impurities, such as Al and Bi, amounted to less than 0.017 wt. %. The natural ageing of the alloy was carried out by keeping the samples in storage for 35 days under atmospheric conditions.

Microstructure of the Pb–0.3%Sn–0.1%Ca negative grid alloy was observed by JEOL JSM-6490 LV scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). The operating voltage of the equipment was set to 20 kV and 30 nA, where the electron beam size was  $\sim 2$   $\mu$ m. Spectra of certain areas of the sample surface was also obtained to analyse the distribution of alloying elements within the alpha-lead solid solution. Grain size of the alloy was determined using an EPIQUANT image analyser with measurement error  $\pm 3$  %.

The alloy specimens were tested in unaged (immediately after casting) and aged conditions (with intervals of 2–7 days) at room temperature. Tensile tests were conducted using a computer controlled TIRAtest 2300 universal testing machine at a constant crosshead speed of 10 mm/min. The stretching force was applied stepwise with a step of 100 N. Standard flat samples with a total length of 60 mm, a gage length of 45 mm, and a thickness of 3 mm from the as-cast alloy and each ageing group were prepared. Ultimate tensile strength ( $\sigma_U$ ), yield strength ( $\sigma_Y$ ), Young's modulus (Y), and elongation ( $\gamma$ ) were calculated from the nominal stress ( $P_H$ ) versus strain elongation ( $\Delta l/l$ ) curves obtained from the tensile test. The results were the average value of six samples in each test group.

## RESULTS AND DISCUSSION

The studied Pb–0.3%Sn–0.1%Ca alloy produces fine grains with serrated grain boundaries, as seen in Fig. 1. Fig. 1b is a higher magnification image of Fig. 1a revealing the intermetallic compounds that are suggested to be primary Pb<sub>3</sub>Ca particles. This phase is also precipitated during cooling at the grain boundaries from the supersaturated alpha-lead solid solution by the process of cellular precipitation [12,33]. Then calcium precipitation can be converted from cellular to continuous precipitation to form more stable and strong (Pb,Sn)<sub>3</sub>Ca particles.



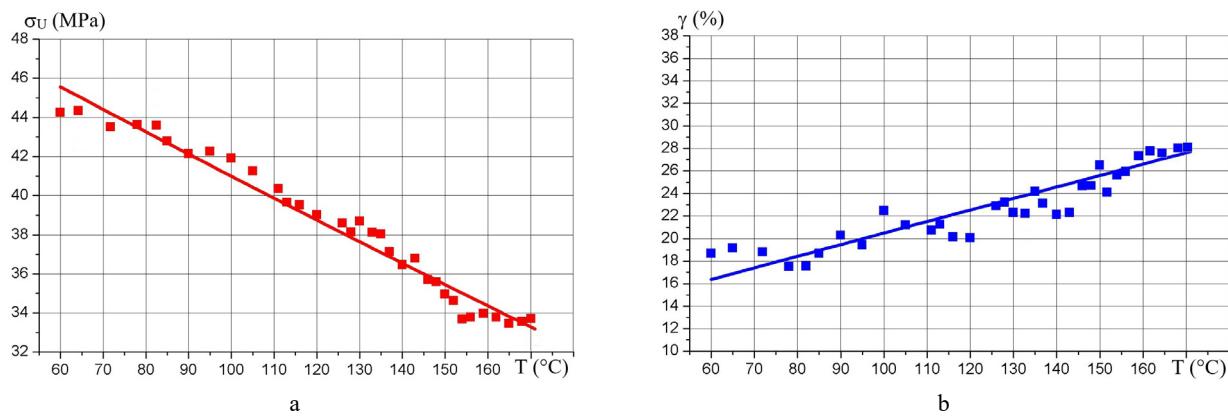
**Figure 1.** Microstructure of Pb–0.3%Sn–0.1%Ca grid alloy: a,b – SEM images at different magnifications; c,d – EDS analysis points across the surface

EDS analyses carried out in the lead-rich matrix of the Pb–0.3%Sn–0.1%Ca alloy (spectra corresponding to the white rectangles in Fig. 1cd) show that calcium can barely be detected around precipitated intermetallic particles, which indicates that calcium is enriched in these precipitates. It is not possible to determine exactly the composition for the intermetallic phases since electron diffraction spectrum comes from both the precipitates and the matrix. Considering the related literature [24,25], it is assumed that the fine phases appearing in the SEM images are the Pb<sub>3</sub>Ca and (Pb,Sn)<sub>3</sub>Ca precipitates.

SEM images combined with EDS results confirm the segregation of some tin at grain boundaries [12]. EDS analysis points across surface of the studied alloy reveal on average 0.45 wt. % Sn at the grain boundaries and in their vicinity (see Spectra 1,3 in Fig. 1c and Spectrum 4 in Fig. 1d). Average tin content near subgrain boundaries increases up to 0.63 wt. % (see Spectrum 5 in Fig. 1d) as compared with that near grain boundaries. But Spectra 8,9,10 in Fig. 1d show that there is no tin at some grain boundaries indicating that the (Pb,Sn)<sub>3</sub>Ca phase has been nucleated here. This means that the alloy does not contain sufficient tin to remain at all grain boundaries. Sometimes, in the grain centre traces of Sn are also not revealed (see Spectrum 2 in Fig. 1c and Spectrum 7 in Fig. 1d).

The average grain size of the Pb–0.3%Sn–0.1%Ca alloy can be significantly increased by rising mould preheating temperature during casting procedure. Higher mould temperature enlarges the grain size from 45±5 µm at 60 °C up to 67±8 µm at 125 °C, and then up to 92±11 µm at 170 °C (by 104 % in all). The increase in grain size is very favourable [34,35] since fine-grained structure is a serious detriment in terms of intergranular corrosion [36–38] which prevails in the lead-tin-calcium grid alloys for lead-acid batteries.

In this investigation, it has been observed that larger grain size of the Pb–0.3%Sn–0.1%Ca negative grid alloy produces lower ultimate tensile strength (by ~25 %) and higher elongation (by ~50 %), as shown in Fig. 2. The temperature dependencies of ultimate tensile strength and elongation are approximately 0.1 MPa/°C and 0.09 %/°C, respectively. At mould temperatures higher than 160±5 °C, there are little variations in the values of these properties.



**Figure 2.** Effects of casting mould temperature on tensile properties of Pb–0.3%Sn–0.1%Ca negative grid alloy:  
a – ultimate tensile strength; b – elongation

Described changes in the values of ultimate tensile strength and elongation are assumed to be due to the formation of larger grains in the alloy's structure as mould preheating temperature increases. The area of grain boundaries impeding dislocation movement decreases, which increases elongation. But when mould temperature related to the cooling rate is higher, cooling conditions are closer to an equilibrium kinetic, resulting in less uniform structure within the lead grains. As known, calcium segregates in the grain centre while tin segregates at the grain boundaries [2]. As a result, the grain boundaries have different composition as that of the grain centre, which reduces values of ultimate tensile strength.

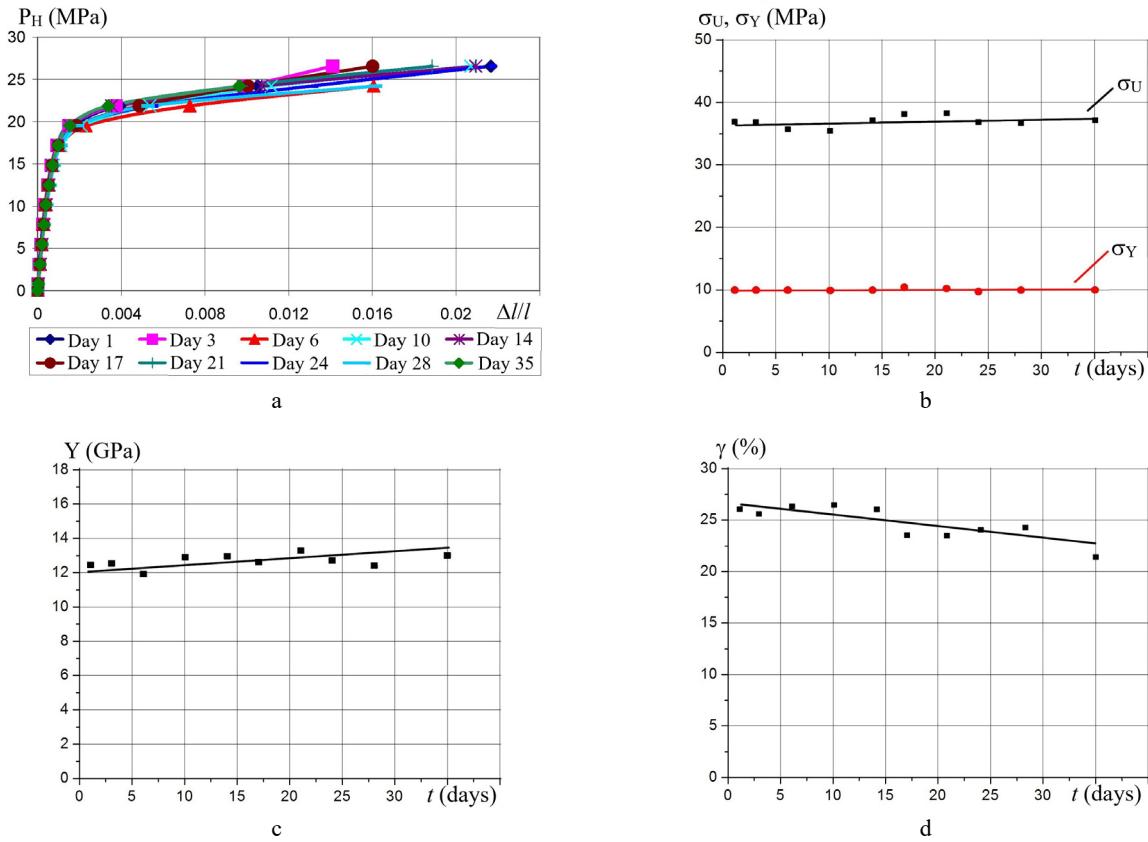
Mould preheating temperature has less effect on ultimate tensile strength as compared with that on elongation due to formation of greater amounts of uniformly dispersed primary Pb<sub>3</sub>Ca particles in the slower cooled alloy that strengthen lead matrix. Formation of these particles is presumed to partially compensate the reduction in the tensile strength. The change in elongation is relatively large since both the resistance to dislocation motion and the promotion of inhomogeneous dislocation multiplication by the precipitates are relatively low [39,40].

Thus, slower cooling can produce two times larger grains in the Pb–0.3%Sn–0.1%Ca grid alloy structure. Whereas natural ageing during storage for 35 days under atmospheric conditions has no appreciable effect on increasing grain size. Furthermore, the alloy has been fully strengthened by ageing during first 1–3 days and cannot be further strengthened by ageing. Such conclusion follows from the stress-strain curves that show a good convergence of tensile test results for specimens aged over a period of 35 days, as illustrated in Fig. 3a.

Ageing of the Pb–0.3%Sn–0.1%Ca grid alloy for 1–3 days increases ultimate tensile strength by 8.8 % and decreases elongation by 7.1 % over their values determined immediately after casting into the mould preheated up to 160±5 °C and air cooling. More stable and strong (Pb,Sn)<sub>3</sub>Ca precipitates are believed to form and strengthen alpha-lead matrix during this ageing stage. The movable capacity of the dislocations decreases resulting in an increase in the alloy's ultimate tensile strength and a decrease in the elongation. But as the formation of these precipitates which can

effectively impede dislocation movement is suggested to occur at a very slow rate, relatively slight changes in these properties are found.

After first 3 days of storage, ageing has insignificant effect on tensile properties, which is confirmed by calculated values of ultimate tensile and yield strengths, Young's modulus, and elongation, as shown in Fig. 3bcd. The changes in values are negligible since ultimate tensile and yield strengths increase from 37.0 MPa to 37.2 MPa (by 0.5 %) and from 10.0 MPa to 10.1 MPa (by 1 %), respectively. Young's modulus also remains almost unchanged and equals to 12.9 GPa on average. Elongation decreases from 26.1 % to 21.5 % (by 17.6 %), which corresponds to embrittlement due to ageing result of the interaction between dislocation and precipitate particles.



**Figure 3.** Effects of ageing time on tensile properties of Pb–0.3%Sn–0.1%Ca negative grid alloy:  
a – stress-strain curves; b – ultimate tensile ( $\sigma_U$ ) and yield ( $\sigma_Y$ ) strengths; c – Young's modulus; d – elongation

Thus, as expected, the Pb–0.3%Sn–0.1%Ca grid alloy strengthens very rapidly, which is in good agreement with previous observations [14,15]. The strength and plasticity of the alloy are closely correlated with the changes in the microstructure. Since the ageing time has little influence on the grain size of the alloy, no significant differences in the values of the tensile properties are found due to the slow precipitation processes with the extension of ageing time. Generally, the characteristics of microstructure evolved in different ageing stages during 35 days in storage contribute to a significant flat tendency in most tensile properties, especially after the ageing time of 1–3 days.

The lower values of yield strength as compared with those of ultimate tensile strength can be attributed to the precipitation of the strengthening phases which consume alloying elements present in the alpha-lead solid solution. As a result, distribution of these elements is less effective in blocking the motion of dislocations within the lead grains and thus weakens the strengthening effects. Ageing also causes a reduction in elongation due to the precipitates formed on the dislocations. As dislocations are pinned by precipitates, higher stress is required for the dislocations to escape the blockage of the precipitates to proceed moving. As a result, dislocations are less uniformly distributed, and deformation is localized, causing a loss of ductility. The ageing time for 35 days is sufficient for dislocations to get locked because the  $\text{Pb}_3\text{Ca}$  and  $(\text{Pb},\text{Sn})_3\text{Ca}$  precipitates, stable against dissolving and coarsening, constitute an effective obstacle for restricting the movable capacity of the dislocations.

So, tin and calcium contents in the studied Pb–0.3%Sn–0.1%Ca negative grid alloy are presumed to form strengthening precipitates, which produces tensile properties required for further processing. Ageing alone contributes very little to the strength of the alloys yet provides more effective level of strengthening when combined with casting conditions. Casting procedure that comprises preheating of the casting mould up to  $160 \pm 5$  °C and further air cooling to room temperature changes ageing kinetics of the Pb–0.3%Sn–0.1%Ca grid alloy. The change is attributed to a decrease in the calcium supersaturation, i.e., the driving force of the precipitation of the strengthening phases after cooling at the

slower rate. Strengthening occurs very rapidly within 1–3 days with the formation of stable  $\text{Pb}_3\text{Ca}$  and  $(\text{Pb},\text{Sn})_3\text{Ca}$  precipitates. The decrease in precipitation rate is believed to be mainly related to the saturation of precipitation because the actual amounts of calcium and tin in the lead-based solution are reduced due to slower cooling and ageing. Thus, in this alloy cast negative grids can be processed within short period after production, which significantly reduces inventory in the enterprise.

## CONCLUSIONS

In this work, the effects of mould preheating temperature and ageing time on grain structure and tensile properties of  $\text{Pb}-0.3\%\text{Sn}-0.1\%\text{Ca}$  alloy for negative grids of lead-acid batteries have been studied. The alloy's grains become two times larger as the mould preheating temperature during casting increases in the range between 60 °C and 170 °C. This is accompanied by the decrease in ultimate tensile strength by ~25 % and the increase in elongation by ~50 %.

The microstructure of the  $\text{Pb}-0.3\%\text{Sn}-0.1\%\text{Ca}$  negative grid alloy remains stable during natural ageing for 35 days, with no noticeable changes in grain size revealed. For the alloy, the age strengthening occurs very quickly since stable values of most tensile properties are reached within 1–3 days. After this period, the alloy continues to strengthen at a negligible rate since a slight decrease in elongation is observed. So, as compared with the effect of mould temperature, ageing time has a minor effect on the  $\text{Pb}-0.3\%\text{Sn}-0.1\%\text{Ca}$  grid alloy microstructure and tensile properties during a period exceeding 3 days.

The  $\text{Pb}-0.3\%\text{Sn}-0.1\%\text{Ca}$  alloy possesses acceptable combination of tensile properties for processability so that the alloy can be made into negative grids using the chosen casting method and be subjected to various lead-acid battery processing and assembly steps.

The work was performed within the framework of research projects of National Academy of Sciences of Ukraine No. 1.3.6.18 “Development of new methods and improvement of known ones to investigate mechanics of transport and energetic systems” (2017-2021) and No. 1.3.6.22 “Development of mathematical models and investigation of ground transport and energetic systems” (2022-2026).

## ORCID

- ✉ Victor O. Dzenzerskiy, <https://orcid.org/0000-0002-9722-1920>; ✉ Sergei V. Tarasov, <https://orcid.org/0000-0002-9254-1503>
- ✉ Olena V. Sukhova, <https://orcid.org/0000-0001-8002-0906>; ✉ Dmytro O. Redchys, <https://orcid.org/0000-0001-8538-6026>
- ✉ Volodymyr A. Ivanov, <https://orcid.org/0009-0008-9836-6508>

## REFERENCES

- [1] S. Guruswamy, *Engineering Properties and Applications of Lead Alloys*, (CRC Press, New York, 2000). <https://doi.org/10.1201/9781482276909>
- [2] D.A.J. Rand, T. Moseley, J. Garche, and C.D. Parker, *Valve-Regulated Lead-Acid Batteries*, (Elsevier, Amsterdam, 2004). <https://doi.org/10.1016/B978-0-444-50746-4.X5000-4>
- [3] V.O. Dzenzerskiy, S.V. Tarasov, D.O. Redchys, V.A. Ivanov, and O.V. Sukhova, *J. Nano- Electron. Phys.* **16**(1), 01003 (2024). [https://doi.org/10.21272/jnep.16\(1\).01003](https://doi.org/10.21272/jnep.16(1).01003)
- [4] J. Jung, L. Zhang, and J. Zhang, *Lead-acid battery technologies: fundamentals, materials, and applications*, (CRC Press, Boca Ranton, 2015), <https://doi.org/10.1201/b18665>
- [5] V.O. Dzenzerskiy, S.V. Tarasov, O.V. Sukhova, and V.A. Ivanov, *East Eur. J. Phys.* **2023**(4), 182 (2023). <https://doi.org/10.26565/2312-4334-2023-4-21>
- [6] V.O. Dzenzerskiy, S.V. Tarasov, O.V. Sukhova, D.O. Redchys, and V.A. Ivanov, *Kovove Mater.* **62**(3), 153 (2024). <https://doi.org/10.31577/km.2024.3.153>
- [7] E. Gullian, L. Albert, and J.L. Caillerie, *J. Power Sources* **116**(1-2), 185 (2003). [http://dx.doi.org/10.1016/S0378-7753\(02\)00705-X](http://dx.doi.org/10.1016/S0378-7753(02)00705-X)
- [8] M.T. Wall, Y. Ren, T. Hesterberg, T. Ellis, and M.L. Young, *J. Energy Storage* **55**, 105569 (2022). <https://doi.org/10.1016/j.est.2022.105569>
- [9] Y.B. Zhou, C.X. Yang, W.F. Zhou, and H.T. Liu, *J. Alloys Compd.* **365**(1-2), 108 (2004). [https://doi.org/10.1016/S0925-8388\(03\)00649-2](https://doi.org/10.1016/S0925-8388(03)00649-2)
- [10] R.K. Shervedani, A.Z. Isfahani, R. Khodavisy, and A. Hatefi-Mehrjardi, *J. Power Sources* **164**(2), 890 (2007). <https://doi.org/10.1016/j.jpowsour.2006.10.105>
- [11] D. Slavkov, B.S. Haran, B.N. Popov, and F. Fleming, *J. Power Sources* **112**(1), 199 (2002). [https://doi.org/10.1016/S0378-7753\(02\)00368-3](https://doi.org/10.1016/S0378-7753(02)00368-3)
- [12] R.D. Prengaman, *J. Power Sources* **67**(1-2), 267 (1997). [https://doi.org/10.1016/S0378-7753\(97\)02512-3](https://doi.org/10.1016/S0378-7753(97)02512-3)
- [13] E. Rocca, G. Bourguignon, and J. Steinmetz, *J. Power Sources* **161**(2), 666 (2006). <http://dx.doi.org/10.1016/j.jpowsour.2006.04.140>
- [14] Z.W. Chen, J.B. See, W.F. Gillian, and D.M. Rice, *J. Power Sources* **42**(1-2), 35 (1993). [https://doi.org/10.1016/0378-7753\(93\)80135-c](https://doi.org/10.1016/0378-7753(93)80135-c)
- [15] L. Muras, P.R. Munroe, S. Blairs, P. Krauklis, Z.W. Chen, and J.B. See, *J. Power Sources* **55**(1), 119 (1995). [https://doi.org/10.1016/0378-7753\(94\)02171-x](https://doi.org/10.1016/0378-7753(94)02171-x)
- [16] C. Camurri, C. Carrasco, O. Prat, R. Mangalaraja, A. Pagliero, and R. Colàs, *Mater. Sci. Technol.* **26**(2), 210 (2010). <https://doi.org/10.1179/174328409x443245>

[17] M. Dehmas, A. Maitre, J.B. Richir, and P. Archambault, *J. Power Sources*, **159**(1), 721 (2006). <https://doi.org/10.1016/j.jpowsour.2005.07.094>

[18] A. Maitre, G. Bourguignon, G. Medjahdi, E. McRae, and M.H. Mathon, *Scr. Mater.* **50**(5), 685 (2004). <https://doi.org/10.1016/j.scriptamat.2003.11.013>

[19] Y.A. Yassine, M. Lakhal, N. Labchir, E. Zantalla, E. Saad, and M. Sannad, *Coat.* **13**(9), 1534 (2023). <https://doi.org/10.3390/coatings13091534>

[20] L. Bouirden, J.P. Hilger, and J. Hertz, *J. Power Sources*, **33**(1-4), 27 (1991). [https://doi.org/10.1016/0378-7753\(91\)85046-Y](https://doi.org/10.1016/0378-7753(91)85046-Y)

[21] C.S. Lakshmi, J.E. Manders, and D.M. Rice, *J. Power Sources*, **73**(1), 23 (1998). [https://doi.org/10.1016/S0378-7753\(98\)00018-4](https://doi.org/10.1016/S0378-7753(98)00018-4)

[22] J. Hilger, *J. Power Sources*, **72**(2), 184 (1998). [https://doi.org/10.1016/s0378-7753\(97\)02711-0](https://doi.org/10.1016/s0378-7753(97)02711-0)

[23] H. Li, W.X. Guo, H.Y. Chen, D.E. Finlow, H.W. Zhou, C.L. Dou, G.M. Xiao, S.G. Peng, W.W. Wei, and H. Wang, *J. Power Sources*, **191**(1), 111 (2009). <https://doi.org/10.1016/j.jpowsour.2008.10.059>

[24] R.D. Prengaman, *J. Power Sources*, **95**(1-2), 224-233 (2001). [https://doi.org/10.1016/S0378-7753\(00\)00620-0](https://doi.org/10.1016/S0378-7753(00)00620-0)

[25] H. Tsubakino, M. Tagami, S. Ioku, and A. Yamamoto, *Metall. Mater. Trans. A*, **27**(6), 1675 (1996). <https://doi.org/10.1007/BF02649824>

[26] K. Sawai, Y. Tsuboi, Y. Okada, M. Shiomi, and S. Osumi, *J. Power Sources*, **179**(2), 799 (2008). <https://doi.org/10.1016/j.jpowsour.2007.12.106>

[27] D.A.J. Rand, D.P. Boden, C.S. Lakshmi, R.R. Nelson, and R.D. Prengaman, *J. Power Sources*, **107**(2), 280 (2002). [https://doi.org/10.1016/S0378-7753\(01\)01083-7](https://doi.org/10.1016/S0378-7753(01)01083-7)

[28] B.O. Trembach, Yu.A. Silchenko, M.G. Sukov, N.B. Ratska, Z.A. Duriagina, I.V. Krasnoshapka, O.V. Kabatskyi, and O.M. Rebrova, *Mater. Sci.* **59**(6), 733 (2024) <https://doi.org/10.1007/s11003-024-00834-2>

[29] B. Trembach, Y. Silchenko, O. Balenko, D. Hlachev, K. Kulahin, H. Heiko, O. Bellorin-Herrera, *et al.*, *Int. J. Adv. Manuf. Technol.* **134**, 309 (2024). <https://doi.org/10.1007/s00170-024-14115-4>

[30] I.M. Spyrydonova, O.V. Sukhova, and G.V. Zinkovskij, *Metall. Min. Ind.* **4**(4), 2 (2012). (in Russian)

[31] Yu.G. Chabak, K. Shimizu, V.G. Efremenko, M.A. Golinskyi, K. Kusumoto, V.I. Zurnadzhy, and A.V. Efremenko, *Int. J. Miner. Metall. Mater.* **29**(1), 78 (2022). <https://doi.org/10.1007/s12613-020-2135-8>

[32] O.V. Sukhova, *Probl. At. Sci. Technol.* **128**(4), 77 (2020). <https://doi.org/10.46813/2020-128-077>.

[33] F. Rossi, M. Lambertin, L. Delfaut-Durut, A. Maitre, and M. Vilasi, *J. Power Sources*, **188**(1), 296 (2009). <https://doi.org/10.1016/j.jpowsour.2008.11.049>

[34] O.V. Sukhova, V.A. Polonskyy, and K.V. Ustinova, *Voprosy Khimii i Khimicheskoi Tekhnologii*. (3), 46 (2019). <http://dx.doi.org/10.32434/0321-4095-2019-124-3-46-52> (in Ukrainian)

[35] O.V. Sukhova, V.A. Polonskyy, and K.V. Ustinova, *Voprosy Khimii i Khimicheskoi Technologii*. (6), 77 (2018). <https://doi.org/10.32434/0321-4095-2018-121-6-77-83> (in Ukrainian)

[36] O.V. Sukhova, and V.A. Polonskyy, *East Eur. J. Phys.* (3), 5 (2020). <https://doi.org/10.26565/2312-4334-2020-3-01>

[37] O.V. Sukhova, V.A. Polonskyy, and K.V. Ustinova, *Mater. Sci.* **55**(2), 291 (2019). <https://doi.org/10.1007/s11003-019-00302-2>

[38] O.V. Sukhova, V.A. Polonskyy, and K.V. Ustinova, *Metallofiz. Noveishie Technol.* **40**(11), 1475 (2018). <https://doi.org/10.15407/mfint.40.11.1475> (in Ukrainian)

[39] V. Lozynskyi, B. Trembach, M.M. Hossain, M.H. Kabir, Y. Silchenko, M. Krbata, K. Sadovy, O. Kolomaitse, and L. Ropyak, *Heliyon*, **10**(3), e25199 (2024). <https://doi.org/10.1016/j.heliyon.2024.e25199>

[40] V.G. Efremenko, A.G. Lekatou, Yu.G. Chabak, B.V. Efremenko, I. Petryshynets, V.I. Zurnadzhy, S. Emmanouilidou, and M. Vojtko, *Mater. Today Commun.* **35**, 105936 (2023). <https://doi.org/10.1016/j.mtcomm.2023.105936.1>

**СТРУКТУРА ТА МЕХАНІЧНІ ВЛАСТИВОСТІ ПРИ РОЗТЯГУВАННІ СПЛАВУ Pb–0,3%Sn–0,1%Ca  
ДЛЯ НЕГАТИВНИХ СТРУМОВІДВОДІВ СВИНЦЕВО-КІСЛОТНИХ АКУМУЛЯТОРІВ**

**Віктор О. Дзензерський, Сергій В. Тарасов, Олена В. Сухова, Дмитро О. Редчиць, Володимир А. Іванов**

*Інститут транспортних систем і технологій Національної академії наук України*

*бул. Писаржевського, 5, 49005, Дніпро, Україна*

Встановлено залежності структури і механічних властивостей при розтягуванні сплаву Pb–0,3%Sn–0,1%Ca для негативних струмовідводів свинцово-кислотних акумуляторів від температури підігріву ливарної форми та тривалості старіння за атмосферних умов. Мікроструктуру сплаву досліджено методами кількісної металографії, скануючої електронної мікроскопії та рентгеноспектрального мікроаналізу. Механічні властивості при розтягуванні, а саме межа міцності на розрив, межа текучості, модуль Юнга і відносне подовження, визначено за кімнатної температури. В разі підвищення температури підігріву ливарної форми в діапазоні від 60 °C до 170 °C межа міцності на розрив зменшується (на ~25 %), а відносне подовження збільшується (на ~50 %) завдяки дворазовому збільшенню розміру зерна в структурі сплаву. Тоді як природне старіння впродовж 35 діб не має суттєвого впливу ні на розмір зерна, ні на механічні властивості при розтягуванні.

**Ключові слова:** свинцово-кислотні акумулятори; негативні струмовідводи; сплав свинець-олово-кальцій; ливарні умови; температура підігріву ливарної форми; природне старіння; розмір зерна; механічні властивості при розтягуванні