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Technical Faculty in Bor,
Mining and Metallurgy
Institute Bor

# 54th International October Conference on Mining and Metallurgy

# PROCEEDINGS

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**Editors:**
Ljubiša Balanović
Dejan Tanikić

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# PREFACE

On behalf of the Organizing Committee, it is a great honor and pleasure to welcome all esteemed participants of the 54th International October Conference on Mining and Metallurgy (IOC 2023), scheduled to take place at the picturesque Bor Lake, Serbia, from October18th to 21st 2023.

The collaborative efforts of the University of Belgrade, the Technical Faculty in Bor, and the Mining and Metallurgy Institute Bor have meticulously organized this year's IOC. Our focus remains unwavering on showcasing the latest research findings and advancements in geology, mining, metallurgy, materials science, technology, environmental protection, and other engineering disciplines. Our primary objective is to foster a dynamic environment where academics, researchers, and industry professionals can come together to share their knowledge, experiences, and innovative ideas while exploring opportunities for collaborative research endeavors.

Our conference agenda is rich and diverse, encompassing plenary sessions, engaging invited lectures, technical presentations, enlightening oral and poster sessions, informative technical tours, a diverse exhibition, and memorable social gatherings. At the heart of this event lies our strong commitment to sustainable development within the mining and metallurgy sector. We are dedicated to exploring ecologically conscious methodologies, responsible resource extraction practices, and cutting-edge technologies that reduce the industry's environmental impact and enhance the well-being of local communities.

The conference proceedings comprise 129 papers authored by individuals from universities, research institutes, and industries in 22 countries. We are proud to welcome participants from Bosnia and Herzegovina, Bulgaria, Canada, China, Croatia, Germany, Greece, India, Iran, Kazakhstan, Libya, North Macedonia, Montenegro, Morocco, Romania, Russia, Slovakia, South Africa, Spain, Turkey, United States, and, of course, Serbia.

We are excited to host the 8th International Student Conference on Technical Sciences (ISC 2023) as part of IOC 2023. This event offers students from Serbia and the wider region a unique chance to showcase their research and discuss the future of their fields with experts.

We sincerely thank the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia for their generous financial support. In addition, we express our profound gratitude to all our sponsors, exhibitors, and friends of the Conference for their contributions and unwavering support for playing a pivotal role in ensuring the success of IOC 2023.

We would like to express our heartfelt thanks to all authors, committees, reviewers, speakers, and chairpersons for their invaluable contributions in shaping IOC 2023.

We look forward to welcoming you to the 55th International October Conference on Mining and Metallurgy (IOC 2024), which will be held in October 2024.

On behalf of the 54th IOC Organizing Committee,

Prof. dr Ljubiša Balanović

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# EFFECT OF CHEMICAL COMPOSITION ON THE CORROSION RESISTANCE OF THE TERNARY Ag-Ge-Sn ALLOYS

**Milena Zečević[1], Duško Minić[1], Aleksandar Đorđević[1], Dragan Manasijević[2]**

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**Abstract**

*In this paper selected system is Ag-Ge-Sn. This system was previously studied by our group. In this paper results are focused on corrosion resistance. Experimental part includes results of the corrosion resistance of the binary alloys Ge50Sn50, Ag50Sn50, Ag50Ge50 and ternary (Ag-Ge-Sn) alloys in 3% NaCl, of the selected ternary Ag-Ge-Sn alloys. The corrosion resistance of these alloys was examined in 3% NaCl solution using the potentiodynamically polarization method (Tafel plots) and electrochemical impedance spectroscopy (EIS). Tafel plots were fitted using the DC Corrosion Technique software. The results of electrochemical impedance spectroscopy (EIS) were fitted using the Gamry Echem Analyst program and the corresponding equivalent circuit. The value of the exponent n was used to determine the degree that controls the rate of the electrochemical reaction. It was investigated how the chemical composition affects corrosion.*

***Keywords**: Metals and alloys, Ag-Ge-Sn system, corrosion resistance*

## 1. INTRODUCTION

Knowledge of corrosion properties of ternary systems based on Ag, Ge and Sn are of great importance due to different applications in the field of energy and electronics and further practical use [1]. Also, Ge-based alloys are necessary for the development of memory materials [2], for the production of optical discs, DVDs, Blue-Ray discs, flash memory, etc. The corrosion resistance of these alloys was examined in 3% NaCl solution using the potentiodynamically polarization method (Tafel plots) and electrochemical impedance spectroscopy (EIS). Tafel plots were fitted using the DC Corrosion Technique software. This paper presents representative results of performed electrochemical measurements. The results of electrochemical corrosion parameters provide the possibility of a clearer understanding of the potential application of the tested alloys. They provide better understanding of practical application of the tested alloys of the ternary Ag-Ge-Sn system.

## 2. EXPERIMENTAL PROCEDURE

All tested samples were prepared from high purity elements: silver, germanium and tin. Samples were melted in an induction furnace under high-purity argon atmosphere and slowly cooled to the room temperature. Total mass of sample were 7 g and the dimension were (15x15x1) mm for corrosion resistance. Such prepared samples are subjected to experimental tests.

Three binary $Ge_{50}Sn_{50}$, $Ag_{50}Sn_{50}$, $Ag_{50}Ge_{50}$ and six ternary $Ag_{45}Ge_{10}Sn_{45}$, $Ag_{30}Ge_{40}Sn_{30}$, $Ag_{65}Ge_{17.5}Sn_{17.5}$, $Ag_{80}Ge_{10}Sn_{10}$, $Ag_{25}Ge_{25}Sn_{50}$, $Ag_{15}Ge_{15}Sn_{70}$ alloys were selected for measurement of corrosion resistance.The corrosion resistance of these materials was examined in 3% NaCl solution using the potentiodynamic polarization method and electrochemical impedance spectroscopy (EIS). Tafel polarizing plots were fitted using the DC Corrosion Technique software. The results of electrochemical impedance spectroscopy (EIS) were fitted using the Gamry Echem Analyst program and the appropriate equivalent circuit.

Electrochemical tests of the corrosion resistance of the alloys in 3% NaCl solution were conducted using potentiodynamic polarization measurements (Tafel diagrams) and measurements of

electrochemical impedance spectroscopy (Nyquist diagrams), on a potentiostat/gavanostat /ZRA Gamry Series GTM 750 with an appropriate software.
Electrochemical methods for corrosion resistance testing are described in detail in the relevant literature [3,4].

## 3. RESULTS AND DISCUSSIONS

Three binary ($Ge_{50}Sn_{50}$, $Ag_{50}Sn_{50}$, $Ag_{50}Ge_{50}$) and six ternary alloys (sample 1 $Ag_{65}Ge_{17.5}Sn_{17.5}$, sample 2 $Ag_{80}Ge_{10}Sn_{10}$, sample 3 $Ag_{45}Ge_{10}Sn_{45}$, sample 4 $Ag_{30}Ge_{40}Sn_{30}$, sample 5 $Ag_{25}Ge_{25}Sn_{50}$ and sample 6 $Ag_{15}Ge_{15}Sn_{70}$) were selected for the corrosion resistance test. Tafel plots are given in Figures 1 and 2, while the corresponding Nyquist diagrams are given in Figures 3 and 4. Tables 1 and 2 show the obtained electrochemical polarization parameters for corrosion.The results for electrochemical impedance corrosion parameters are shown in Tables 4 and 4.

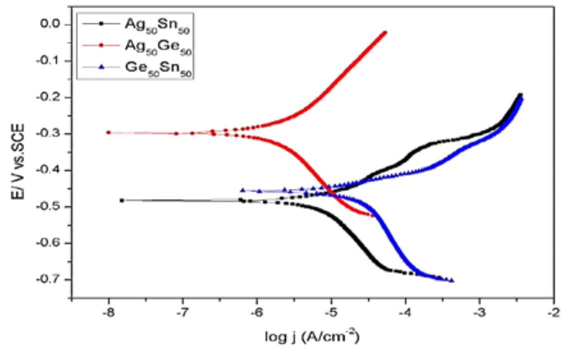


Figure 1 - Tafel plots for tested binary alloys $Ge_{50}Sn_{50}$, $Ag_{50}Ge_{50}$ and $Ag_{50}Sn_{50}$

Table 1 - Electrochemical polarization parameters of corrosion for tested binary alloys $Ge_{50}Sn_{50}$, $Ag_{50}Ge_{50}$ and $Ag_{50}Sn_{50}$

| Alloy | Predicted percent of the phase at 25 °C | $-E_{corr}$ (mV) | $j_{corr}$ (μA/cm$^2$) | $v_{corr}$ (mm/year) | βa (mV/dec) | βk (mV/dec) |
|---|---|---|---|---|---|---|
| B1, $Ge_{50}Sn_{50}$ | 50%(Ge)+50%(βSn) | 456 | 16,10 | 0,54 | 73,40 | 105,8 |
| B2, $Ag_{50}Sn_{50}$ | 33%(βSn)+67%ε | 482 | 2,940 | 0,098 | 37,40 | 57,90 |
| B3, $Ag_{50}Ge_{50}$ | 50%(Ag)+50%(Ge) | 296 | 1,060 | 0,035 | 84,40 | 114,3 |

From the presented data (Figure 1 and Table 1) for the tested samples of three binary alloys B1 $Ge_{50}Sn_{50}$, B2 $Ag_{50}Sn_{50}$ and B3 $Ag_{50}Ge_{50}$ it is evident that the corrosion potentials of $E_{corr}$ range from -296 mV for B3 $Ag_{50}Ge_{50}$ to -482 mV for B2 $Ag_{50}Sn_{50}$. The $j_{corr}$ corrosion current densities range from 1,060 μA/cm$^2$ for B3 $Ag_{50}Ge_{50}$ to 16.10 μA/cm$^2$ for B1 $Ge_{50}Sn_{50}$. The lowest value of corrosion rate $v_{corr}$=0.035 mm/year is for the binary alloy B3 $Ag_{50}Ge_{50}$, which is more corrosion resistant than the binary alloy B1 $Ge_{50}Sn_{50}$ ($v_{corr}$=0.54 mm/year) and the binary alloy B2 $Ag_{50}Sn_{50}$ ($v_{corr}$=0.098 mm/year), which has the highest value of the corrosion rate of the three binary alloys tested.

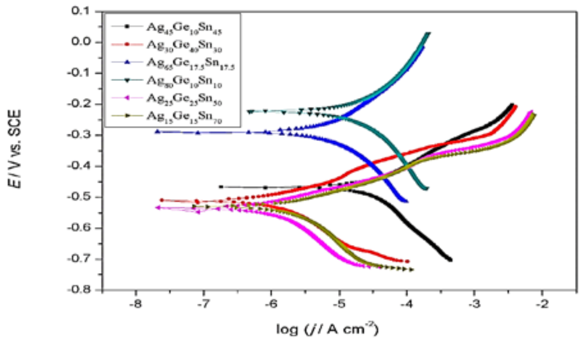


Figure 2 - Tafel plots for tested ternary alloys Ag-Ge-Sn

Table 2 - Electrochemical polarization parameters of corrosion for tested ternary alloys Ag-Ge-Sn

| Alloy | Predicted percent of the phase at 25 °C | $-E_{corr}$ (mV) | $j_{corr}$ (μA/cm$^2$) | $v_{corr}$ (mm/year) | βa (mV/dec) | βk (mV/dec) |
|---|---|---|---|---|---|---|
| 1 - $Ag_{65}Ge_{17,5}Sn_{17,5}$ | 17%(Ge)+53%ε+30%ζ | 289 | 0,94 | 0,031 | 32,66 | 67,76 |
| 2 - $Ag_{80}Ge_{10}Sn_{10}$ | 10%(Ge)+90%ζ | 224 | 2,67 | 0,089 | 33,66 | 68,61 |
| 3 - $Ag_{45}Ge_{10}Sn_{45}$ | 30%(βSn)+10%(Ge)+60%ε | 466 | 3,859 | 0,129 | 25,33 | 67,22 |
| 4 - $Ag_{30}Ge_{40}Sn_{30}$ | 20%(βSn)+40%(Ge)+40%ε | 509 | 0,16 | 0,005 | 24,39 | 49,77 |
| 5 - $Ag_{25}Ge_{25}Sn_{50}$ | 42%(βSn)+25%(Ge)+33%ε | 533 | 0,22 | 0,007 | 38,58 | 53,59 |
| 6 - $Ag_{15}Ge_{15}Sn_{70}$ | 65%(βSn)+15%(Ge)+20%ε | 529 | 0,42 | 0,013 | 37,12 | 51,33 |

Based on the presented data (Figure 2 and Table 2) of the tested alloys of the ternary Ag-Ge-Sn system, the highest corrosion resistance was shown by sample 4 ($Ag_{30}Ge_{40}Sn_{30}$), with corrosion potential $E_{corr}$=-509 *mV*, the lowest corrosion density $_{corr}$=0,16 *μA/cm$^2$* and the lowest corrosion rate $v_{corr}$ 0.005 *mm/year*. This can be related to high percent of (Ge) phase inside this sample. Compared with other samples percent of (Ge) phase is highest in sample 4 and then decreases. Sample 5 ($Ag_{25}Ge_{25}Sn_{50}$) also show very high corrosion resistance, where the corrosion current densities are $j_{corr}$=0.22 *μA/cm$^2$* and corrosion rate $v_{corr}$=0,007 *mm/year*. Based on the corrosion current density and the calculated depth indicator of corrosion-corrosion rate $v_{corr}$, all tested alloys are very resistant to corrosion ($v_{corr}$=0.005-0.129 *mm / year*) in 3% NaCl solution. The corrosion resistance of the tested alloys decreases in the following order: sample 4($Ag_{30}Ge_{40}Sn_{30}$), 5($Ag_{25}Ge_{25}Sn_{50}$), 6($Ag_{15}Ge_{15}Sn_{70}$) 1($Ag_{65}Ge_{17.5}Sn_{17.5}$), 2($Ag_{80}Ge_{10}Sn_{10}$) and 3 ($Ag_{45}Ge_{10}Sn_{45}$). Similar trend is relating to reduction of (Ge) phase: 4, 5, 1, 6, 2 and 3.

Nyquist diagrams for three samples of binary alloys and six samples of ternary alloys were recorded by electrochemical impedance spectroscopy (EIS) (Figures 3 and 4). The fitting of the experimental data was done using an equivalent circuit (Figure 5) and the results (electrochemical impedance corrosion parameters) are shown in Tables 3 and 4.

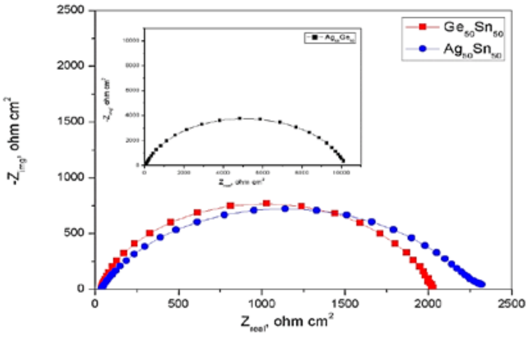


Figure 3 - Nyquist diagrams for tested binary alloys B1-$Ge_{50}Sn_{50}$, B2-$Ag_{50}Sn_{50}$ and B3-$Ag_{50}Ge_{50}$.

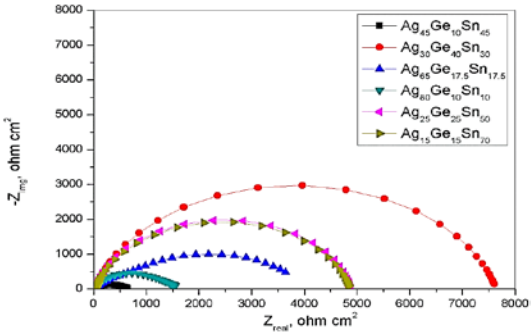


Figure 4 - Nyquist diagrams for tested ternary alloys of the Ag-Ge-Sn system.

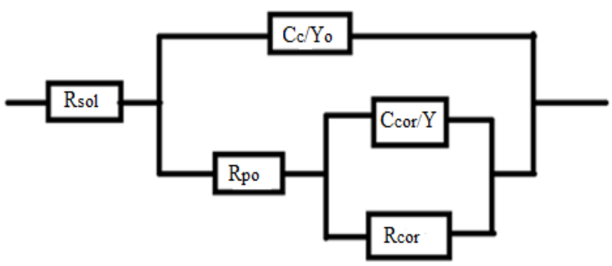


Figure 5 - Equivalent circuit

Table 3. Electrochemical impedance corrosion parameters for tested binary alloys B1-$Ge_{50}Sn_{50}$, B2-$Ag_{50}Sn_{50}$ and B3-$Ag_{50}Ge_{50}$.

| Alloy | $R_{soln}$, (Ω) | $R_{cor}$, (Ω) | $R_{po}$, (Ω) | $R_{tot.}$(Ω) | $C_{cor}$,(F) | n | $C_c$,(F) | m | Fitting error |
|---|---|---|---|---|---|---|---|---|---|
| B1-$Ge_{50}Sn_{50}$ | 65,15 | 635,3 | 1672 | 2307,3 | $9{,}70\cdot10^{-4}$ | 0,846 | $2{,}10\cdot10^{-5}$ | 0,773 | $2{,}985\cdot10^{-4}$ |
| B2-$Ag_{50}Sn_{50}$ | 35,41 | 3233 | 1870 | 5103,0 | $1{,}52\cdot10^{-2}$ | 0,525 | $6{,}34\cdot10^{-6}$ | 0,743 | $1{,}598\cdot10^{-4}$ |
| B3-$Ag_{50}Ge_{50}$ | 34,94 | 10050 | 142,4 | 10 192,4 | $1{,}16\cdot10^{-5}$ | 0,745 | $6{,}06\cdot10^{-6}$ | 0,901 | $1{,}090\cdot10^{-3}$ |

Table 4. Electrochemical impedance corrosion parameters for tested ternary alloys of the Ag-Ge-Sn sytem.

| Alloy | $R_{soln}$,(Ω) | $R_{cor}$,(Ω) | $R_{po}$,(Ω) | $R_{tot}$,(Ω) | $C_{cor}$,(F) | n | $C_c$,(F) | m | Fitting error |
|---|---|---|---|---|---|---|---|---|---|
| 3-$Ag_{65}Ge_{17,5}Sn_{17,5}$ | 25,42 | 3263 | 770,5 | 4033,5 | $2{,}93\cdot10^{-4}$ | 0,6159 | $2{,}39\cdot10^{-5}$ | 0,7286 | $366{,}8\cdot10^{-6}$ |
| 4-$Ag_{80}Ge_{10}Sn_{10}$ | 24,29 | 1672 | 25,56 | 1697,56 | $2{,}51\cdot10^{-5}$ | 0,3477 | $2{,}94\cdot10^{-5}$ | 0,8922 | $150{,}2\cdot10^{-6}$ |
| 5-$Ag_{45}Ge_{10}Sn_{45}$ | 32,45 | 642,7 | 171,4 | 814,1 | $1{,}41\cdot10^{-5}$ | 0,4133 | $4.55\cdot10^{-6}$ | 0,9635 | $1.521\cdot10^{-3}$ |
| 6-$Ag_{30}Ge_{40}Sn_{30}$ | 27,53 | 6567 | 943 | 7510 | $3{,}79\cdot10^{-6}$ | 0,8792 | $1{,}13\cdot10^{-5}$ | 0,8765 | $2{,}541\cdot10^{-3}$ |
| 11-$Ag_{25}Ge_{25}Sn_{50}$ | 26,88 | 398,3 | 4457 | 4855,3 | $1{,}22\cdot10^{-4}$ | 0,9899 | $1{,}30\cdot10^{-6}$ | 0,8835 | $3{,}269\cdot10^{-4}$ |
| 12-$Ag_{15}Ge_{15}Sn_{70}$ | 26,32 | 3234 | 1605 | 4839 | $1{,}54\cdot10^{-6}$ | 0,9613 | $2{,}38\cdot10^{-5}$ | 0,8531 | $4.245\cdot10^{-3}$ |

For the analyzed data using the equivalent circuit of Figure 5, a low value of the error estimation of the fitting procedure was obtained (Tables 3 and 4). It can be concluded that the selected equivalent circuit is sufficiently precise to describe the tested alloys.

## 4. CONCLUSION

The corrosion resistance of six ternary and three binary alloys was examined in 3% NaCl solution using the potentiodynamically polarization method (Tafel plots) and electrochemical impedance spectroscopy (EIS). The highest corrosion resistance is for sample 6 (Ag30Ge40Sn30).

## ACKNOWLEDGEMENTS

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