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A. DJORDJEVIĆ[1], M. ZEČEVIĆ[1*], D. MINIĆ[1], M. KOLAREVIĆ[2], L. BALANOVIC[3],
D. MANASIJEVIC[3], M. PETROVIĆ[1]

CHARACTERIZATION OF THE Gu-Ge-In: MICROSTRUCTURAL, MECHANICAL, ELECTRICAL PROPERTIES, SCHEIL AND LEVER SIMULATION

Based on application of Cu-based alloys and special application of Ge-based alloys it is from huge interest to study properties of the Cu-Ge-X alloys. In this paper selected system is Cu-Ge-In. This system was previously studied by our group. In this paper results are focused on electrical and mechanical properties. Experimental tests were performed on 12 ternary alloys. Six different experimental techniques were used to test the ternary alloys. The microstructure was tested using light optical microscopy (LOM) and scanning electron microscopy (SEM). The composition of the phases and the composition of the alloys were examined by energy dispersive spectroscopy (EDS). X-ray diffractometric analysis (XRD) was used to determine the phases. Properties such as hardness and electrical conductivity tests were performed. Those properties were used for calculation and modeling those properties along all composition ranges. Isothermal section at 25°C were predicted. Calculated isothermal section and were compared with results of the EDS and XRD test. Good agreement of calculated and experimental result has been reached. Best results of electrical conductivity and hardness give alloys with composition $Cu_{80.93}Ge_{9.86}In_{9.21}$.

Keywords: Isothermal section at 25°C; mechanical and electrical properties; microstructure test; mathematical modeling

1. Introduction

The ternary Cu-Ge-In system has been previously investigated by our group [1,2]. In reference Milosavljevic et al. [1] reliable thermodynamic set has been established. Results of the mechanical and electrical properties of the Cu-Ge-In and Cu-Ge-Pb alloys were summarized in reference [2].

Due to the wide application of Cu [3-5] and Ge [6-8] based alloys, as much as possible information about Cu-Ge-X based alloys are important for future application of Cu-Ge-based alloys. This wide application is based on good properties (such as strength, good electrical conductivity, thermal conductivity etc.) of copper and germanium [9-12]. Those elements, especially copper have been tested for a long by using different techniques [13-15]. Due to the fact that all copper alloys have good properties it is essential to study especially electrical properties of as much as possible Cu alloys.

In this paper, experimental test was performed and calculation of isothermal section at 25°C. By using our previous results given in reference [1], isothermal section at 25°C were predicted. Results of phase equilibrium of isothermal section were compared with results of EDS test. Microstructure of 12 ternary alloys were observed by light optical (LOM) and scanning electron (SEM) microscopy while phases were determined by XRD. On such equilibrium alloys at 25°C, properties as hardness and electrical conductivity were measured. Those properties were measured in three or four different point in same sample and average values were used for mathematical modeling of those properties. According to the result of hardness and electrical conductivity best properties are observed for $Cu_{80.93}Ge_{9.86}In_{9.21}$ alloy. By using Pandat software Scheil and Lever simulation were calculated for $Cu_{80.93}Ge_{9.86}In_{9.21}$ alloy.

Obtained results are necessary information for future tests on this system and also a starting point for tests on high order systems. The sustainability of the obtained results is limitless. Up to this paper there is no information about properties of Cu-Ge-In alloys. Beside presented information of properties it is given mathematical models for calculations of properties along all composition ranges which are important to save time and cost in future property tests.

1 UNIVERSITY OF PRISHTINA IN KOSOVSKA MITROVICA, FACULTY OF TECHNICAL SCIENCE, DEPARTMENT OF TECHNOLOGICAL ENGINEERING, SERBIA
2 UNIVERSITY OF KRAGUJEVAC, FACULTY OF MECHANICAL ENGINEERING IN KRALJEVO, SERBIA
3 UNIVERSITY OF BELGRADE, TECHNICAL FACULTY IN BOR, BOR, SERBIA

* Corresponding author: milena.premovic@gmail.com

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2. Experimental procedure

Standard experimental procedure for metallographic examinations were employed in preparation of 12 ternary alloys [1,2]. On Fig. 1, scheme of experimental procedure has been presented.

Ternary samples were prepared by using high purity Cu, Ge and In starting metals (produced by Alfa Aesar, Germany) with the total masses of the samples about 3 g. Weighted masses of the pure metals were arc-melted and re-melted five times under a high purity argon atmosphere using a non-consumable tungsten electrode. The average weight loss during melting was about 0.5% of the total weight.

Such prepared samples were divided into two groups. The first group of samples was powdered and subjected to the XRD analysis using D2 PHASER, Bruker, Germany powder diffractometer equipped with a dynamic scintillation detector and ceramic x-ray Cu tube (KFL-Cu-2 K). XRD patterns were recorded in a 2θ range from 5 to 75° with a step size of 0.02° and patterns were analyzed using the Topas 4.2 software, ICDD databases PDF2 (2013).

Samples from second group was sealed in the polymer, grinded by using sand paper, then polished using a diamond paste, and finally cleaned in an ultrasonic bath. Such prepared samples were used for light optical microscopy, SEM-ED, hardness and electrical conductivity tests. Used devices for LOM was OLYMPUS microscope. Used device for SEM-EDS analysis was JEOL JSM-6460 scanning electron microscope with energy dispersive spectroscopy (EDS) (Oxford Instruments X-act). The overall compositions of samples were determined by mapping the entire polished surface of the samples. In contrast, the compositions of the observed coexisting phases were determined by examining the surface of the same phase in different parts of the sample. Electrical conductivity measurements were carried out using Foerster SIGMATEST 2.069 eddy instrument. Hardness of the samples were measured using Brinell hard-ness tester INNOVATEST, model NEXUS 3001 with loading conditions force 306.4 N and indented diameter of 2.5 mm.

3. Results and discussions

Prepared sample by procedure given on figure 1, are subjected to the different experimental tests. One group of samples were teste by XRD test in way to determined phases presented in microstructure.

Second group of samples were metallographically prepared by grinding, polishing and cleaning. Such samples were firstly observed by LOM and then by SEM. By using SEM-EDS tests composition of elements inside samples were determined and compositions of elements inside phases. Results of EDS test was used for construction of the isothermal section at 25°C. At the end samples were subjected to the electrical conductivity tests and hardness test. Results of all experimental tests are summarized in next part.

3.1. Phase information

According to the literature information in the ternary Cu-Ge-In system 13 phases should appear. List of those phases together with crystal structure are presented in TABLE 1 [16-26].

3.1.1. XRD, LOM and SEM-EDS analysis

Result of the XRD and EDS test were summarized in TABLE 2. Sample numbers are given in column 1, column 2 are nominal composition, column 3 experimental determined composition of samples by EDS, and last column summary of determined phases by XRD and EDS tests.

Obtained results of XRD and EDS tests, shows existence of four phase regions. Determined regions are consists of three phases. Phase region (Ge) + (In) + $Cu_{11}In_9$ is determined with samples 1, 5-8, and 10-12. Phase region η'' + (Ge) + $Cu_{11}In_9$ is determined with sample 2. Phase region η + η'' + (Ge) is de-

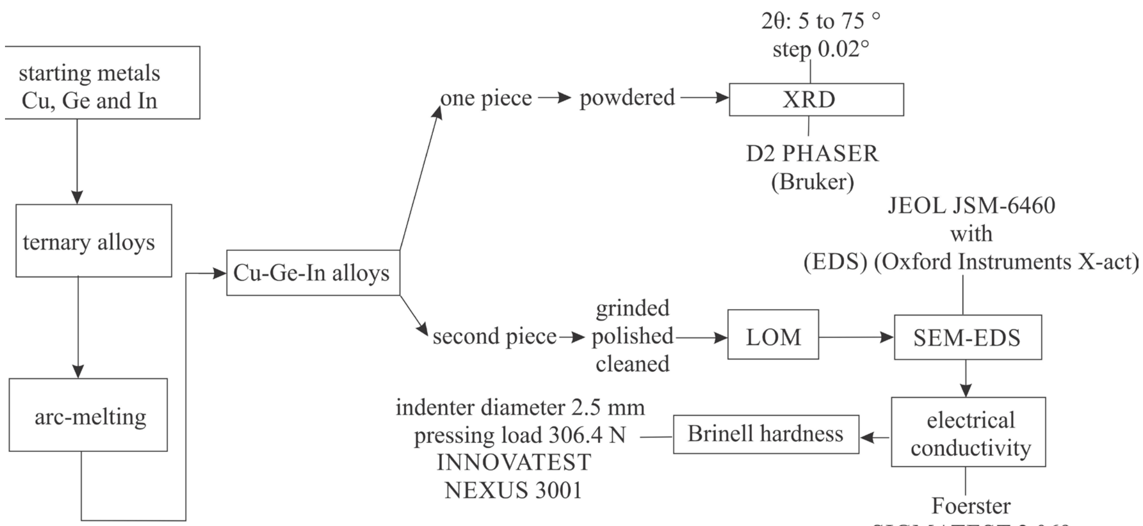

Fig. 1. Scheme of experimental procedure

TABLE 1

List of the 13 solid phases of the ternary Cu-Ge-In system

Phase	Temperature °C	Composition range	Space group	Pearson's symbol	Lattice parameters Å	Ref
(Cu)	<1084	88.3-100 at.% Cu	$Fm\bar{3}m$	$cF4$	$a = b = c = 3.6573$	[16]
(Ge)	<938.2	100 at.% Ge	$Fd\bar{3}m$	$cF8$	$a = b = c = 5.65675$	[17]
(In)	<156.6	100 at.% In	$I4$/mmm	$tI2$	$a = b = 3.2523$ $c = 4.9461$	[18]
ξ	23.5-824.2	83.5-90.2 at.% Cu 16.5-9.8 at.% Ge	$P6_3$/mmc	$hP2$	$a = b = 2.612$ $c = 4.231$	[19]
ε	549.3-749	76.5 at % Cu 23.5 at.% Ge	$P6_3$/mmc	…	$a = b = 4.169$ $c = 7.499$	[20]
η	<674.5	75 at.% Cu 25 at.% Ge	$Pmnm$	$oP8$	$a = 5.29$ $b = 4.20$ $c = 4.55$	[21]
θ	611.6-697.3	73.5 at.% Cu 26.5 at.% Ge	$Fm\bar{3}m$	$cI2$	$a = b = c = 5.906$	[22]
β	567.6-711.2	81.3-77.0 at.% Cu 18.7-23.0 at.% In	$Im\bar{3}m$	$cI2$	$a = b = c = 2.9902(7)$	[23]
γ	612.6-688.0	72.0-68.2 at.% Cu 28.0-31.8 at.% In	$P\bar{4}3m$	$cP52$	$a = b = c = 9.097$	[23]
δ	<632.3	70 at.% Cu 30 at.% In	$P\bar{1}$	$aP40$	$a = 6.733$ $b = 9.134$ $c = 10.074$	[24]
η'	294.8-668.7	66.3-62.3 at.% Cu 33.7-37.7 at.% In	$P6_3$/mmc	$hP6$	$a = b = 4.250$ $c = 4.965$	[25]
η"	<390	64 at.% Cu 36 at.% In	$P6_3$/mmc	$hP4$	$a = b = 4.2943$ $c = 5.2328$	[23]
$Cu_{11}In_9$	<306.6	55 at.% Cu 45 at.% In	$C2/m$	$mC20$	$a = 12.814$ $b = 4.3543$ $c = 7.353$	[26]

TABLE 2

Experimental result of XRD and EDS test of ternary Cu-Ge-In alloys

N.	Nominal composition (atomic fraction)			Composition of samples by EDS (at. %)			Determined phases	
	x(Cu)	x(Ge)	x(In)	x(Cu)	x(Ge)	x(In)	XRD	EDS
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	0.2	0.4	0.4	19.81	40.01	40.18	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$
2	0.4	0.3	0.3	39.32	29.91	30.77	η" (Ge) $Cu_{11}In_9$	η" (Ge) $Cu_{11}In_9$
3	0.6	0.2	0.2	59.72	19.73	20.55	η η" (Ge)	η η" (Ge)
4	0.8	0.1	0.1	80.93	9.86	9.21	η δ ξ	η δ ξ
5	0.4	0.2	0.4	39.15	20.16	40.69	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$
6	0.3	0.4	0.3	30.53	39.34	30.13	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$
7	0.2	0.6	0.2	20.18	60.37	19.45	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$

TABLE 2. Continued

1	2	3	4	5	6	7	8	9
8	0.1	0.8	0.1	10.19	80.78	9.03	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$
9	0.4	0.4	0.2	39.81	39.48	20.71	η η'' (Ge)	η η'' (Ge)
10	0.3	0.3	0.4	30.15	29.34	40.51	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$
11	0.2	0.2	0.6	19.91	19.33	60.76	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$
12	0.1	0.1	0.8	9.52	10.03	80.45	(In) (Ge) $Cu_{11}In_9$	(In) (Ge) $Cu_{11}In_9$

termined with samples 3 and 9. Phase region δ + ξ + η is determined with sample 4.

By using thermodynamic dataset from ref. [1], isothermal section at 25°C is calculated and presented in Fig. 2. Calculated isothermal section at 25°C is compared with EDS results given in TABLE 2.

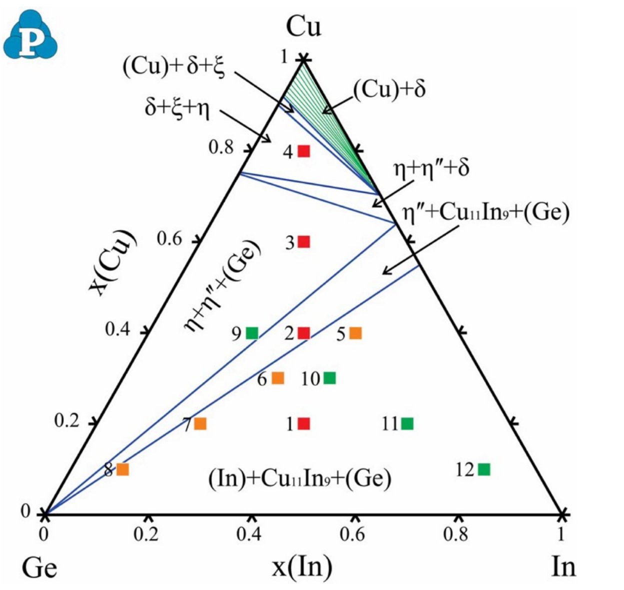

Fig. 2. Comparison of predicted isothermal section at 25°C and experimental results of EDS tests

On isothermal section at 25°C twelve different phase regions are visible. Four of twelve are experimentally confirmed. Three microstructures recorded by LOM are shown on Fig. 3.

Microstructures of samples 2, 3 and 6, shows existence of three phases. In microstructure of sample 2 detected three phases are (Ge) as a gray phase, $Cu_{11}In_9$ as a light needle phase and η'' as a light gray phase. In microstructure of the sample 3, (Ge) appears as a gray phase, η'' is a light gray phase and η is a oval phase. In microstructure of sample 6, (Ge) is a gray phase, (In) as a light gray phase and $Cu_{11}In_9$ phase as a light needle phase.

3.1.2. Mechanical properties

Experimentally determined value of Brinell hardness are summarized in TABLE 3. In last column are given mean value based on three measurements. By using Pandat software fractions of phases inside each sample were calculated (column 2).

Graphical presentation of the Brinell hardness experimentally determined values are given on Fig. 4.

Best hardness from all tested ternary samples have sample 4. Sample 4, have high content of copper 0.8 mol, and in this sample three phases are detected η, δ and ξ. This microstructure has 22.67% of the η phase, 33.33% of the δ phase and 44% of the ξ phase. It is clear that in this microstructure three intermetallic compound give best hardness.

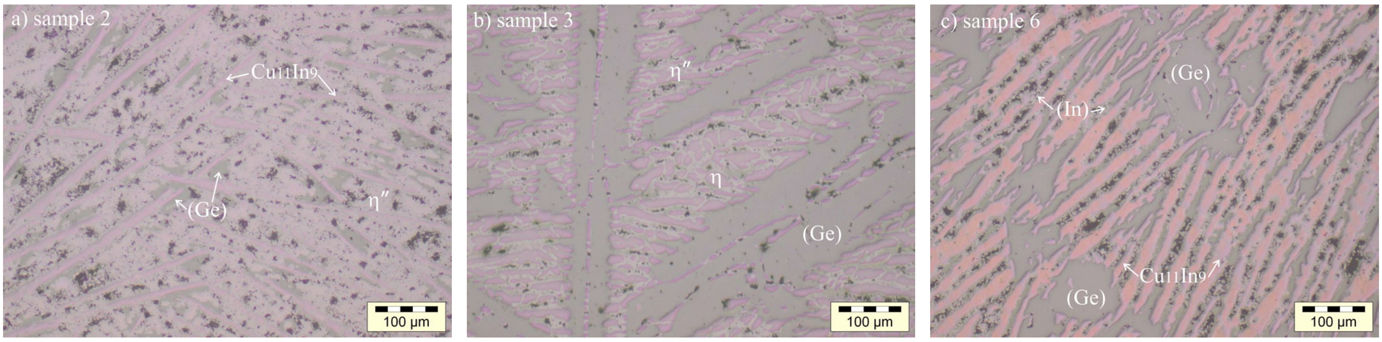

Fig. 3. LOM micrographs of samples a) 2, b) 3 and c) 6

TABLE 3

Phase fraction, experimental Brinell hardness values of three measurement and mean value of tested ternary Cu-Ge-In samples

N.	Calculated fraction of phases	Measured value (MN/m^2)			Mean value (MN/m^2)
		1	2	3	
B1	50% (In) 50% (Ge)	243.80	249.60	246.30	246.43
1	23.64 % (In) 40% (Ge) 36.36% $Cu_{11}In_9$	39.3	34.1	33.3	35.56
2	16.67% η" 30% (Ge) 53.33% $Cu_{11}In_9$	198.9	189.7	192.7	193.76
3	32.59% η 55.56% η" 11.85% (Ge)	608.4	622.5	615.8	615.56
4	22.67% η 33.33% δ 44% ξ	811.5	818.92	816.18	815.53
Cu	100% (Cu)				874.0 [27]
B2	50% (In) 50% (Cu)	194.6	189.7	190.6	191.63
5	7.27% (In) 20% (Ge) 72.73% $Cu_{11}In_9$	165.5	133.3	129.8	142.86
6	5.45% (In) 40% (Ge) 54.55% $Cu_{11}In_9$	204.1	228.3	210.1	214.16
7	3.64% (In) 60% (Ge) 36.36% $Cu_{11}In_9$	634.6	651.2	640.0	641.93
8	1.82% (In) 80% (Ge) 18.18% $Cu_{11}In_9$	666.5	673.1	670.5	670.03
Ge	100% (Ge)				973.40 [27]
B3	50% (Cu) 50% (Ge)	603.8	588.8	623.7	605.43
9	5.93% η 55.55% η" 38.52% (Ge)	264.7	307.0	288.8	286.83
10	15.45% (In) 30% (Ge) 54.55% $Cu_{11}In_9$	103.0	84.3	98.2	95.16
11	43.64% (In) 20% (Ge) 36.36% $Cu_{11}In_9$	23.3	21.2	22.5	22.33
12	71.82% (In) 10% (Ge) 18.18% $Cu_{11}In_9$	12.4	9.9	10.7	11.00
In	100% (In)				8.83 [27]

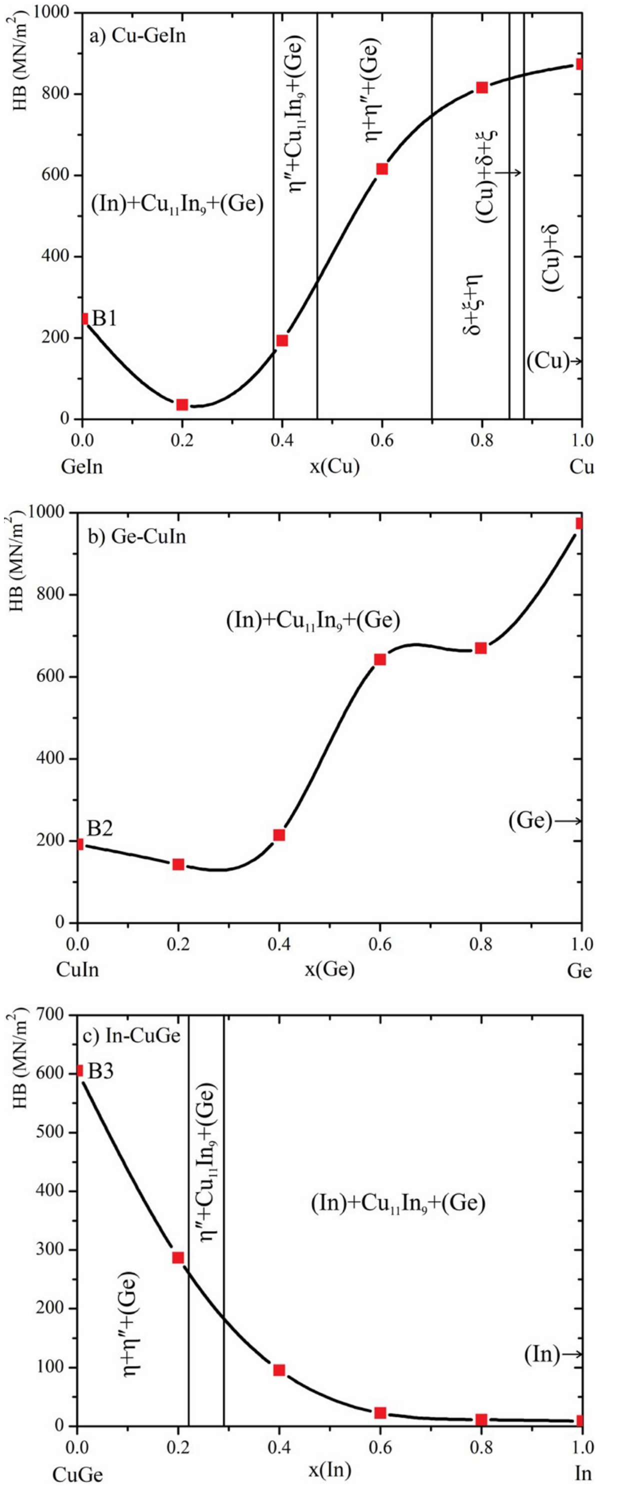

Fig. 4. Experimentally determined Brinell hardness value: a) samples 1 to 4, b) samples 5 to 8 and c) samples 9 to 12

In samples 1, 5, 6, 7, 8, 10, 11 and 12 three phase region (Ge) + (In) + $Cu_{11}In_9$ is dominant. Based on results of the hardness test and results of the phase fraction it is visible how important role is related to the microstructure of alloys and percent of phases. From TABLE 3 it is visible that in this sample 8, (Ge) solid phase is predominant with 80%, while left over are 1.82% (In) solid solution and 18.18% $Cu_{11}In_9$ intermetallic compound. Detected hardness for sample 8 is 666.5, 670.5 and 673.1 MN/m^2 (mean value 670.03 MN/m^2). On Fig. 5 few important diagrams od scheil simulations are calculated by using Pandat software for sample 8.

Beside Scheil simulation for sample 8 are calculated diagrams for solidification, fraction of each solid phases and heat evolution by using Lever simulation. Calculations were done by using Pandat software and presented on Fig. 6.

As a next step it is proposed mathematical model for calculation of the hardness along all composition ranges of ternary Cu-Ge-In alloys. By using software package Design Expert

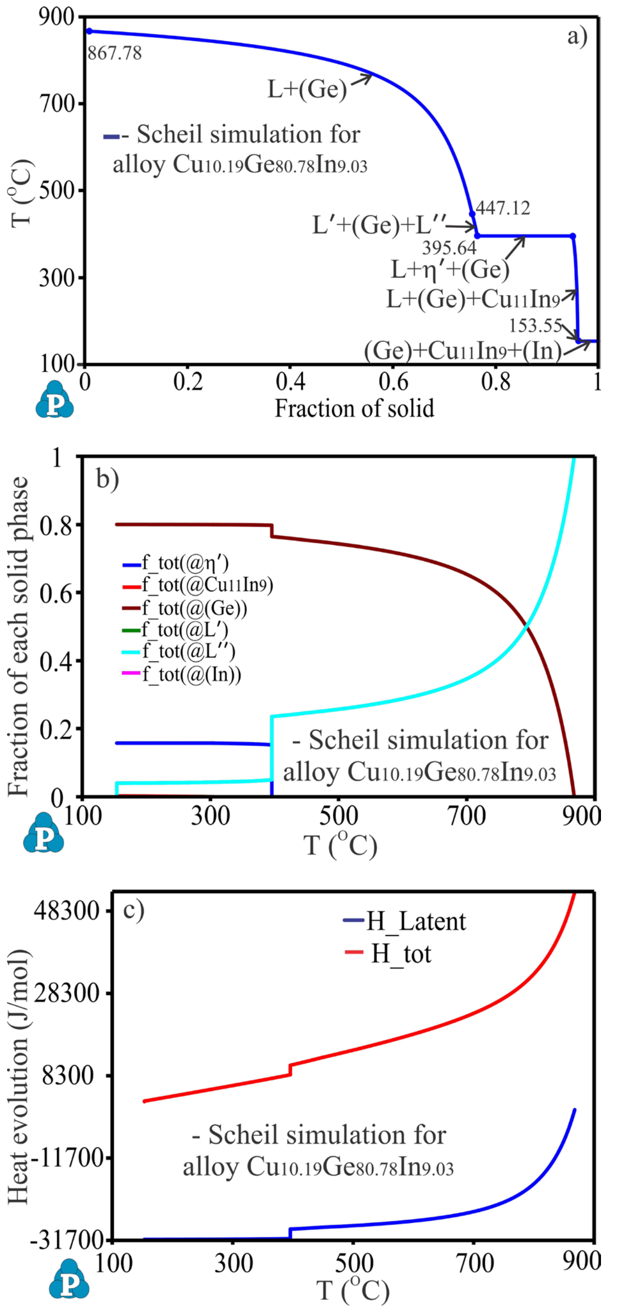

Fig. 5. Scheil simulation for sample 8, alloy $Cu_{10.19}Ge_{80.78}In_{9.03}$ a) fraction of solid, b) fraction of each solid phase and c) heat evolution latent and total

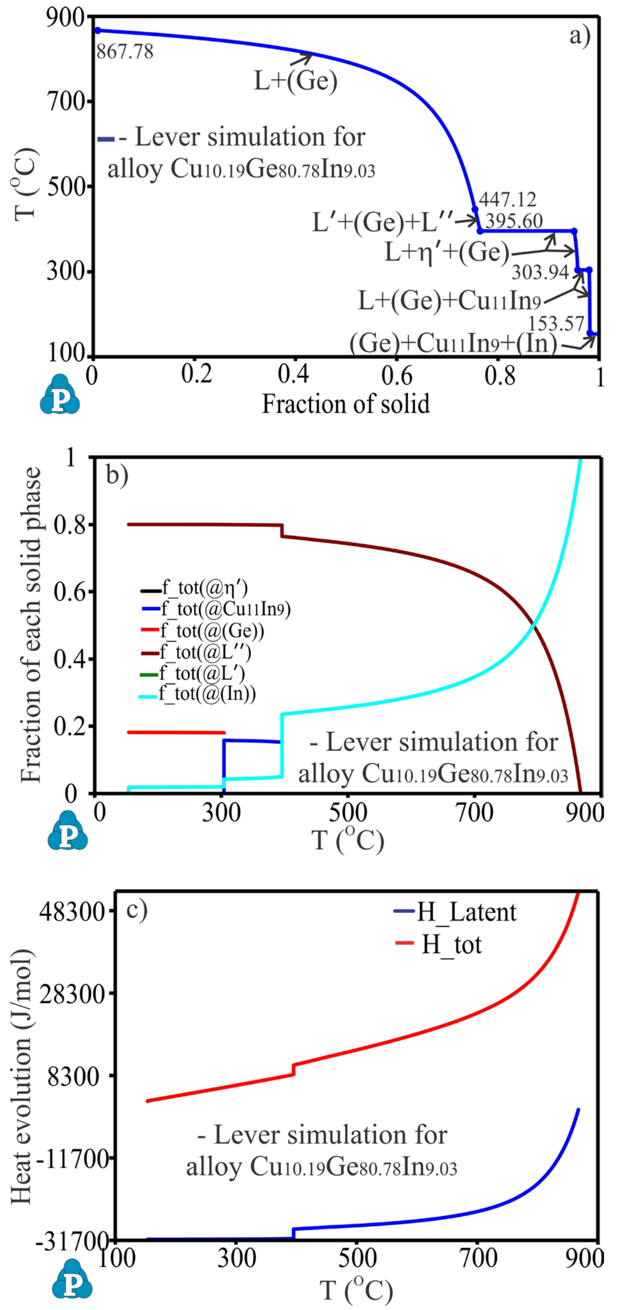

Fig. 6. Lever simulation for sample 8, alloy $Cu_{10.19}Ge_{80.78}In_{9.03}$ a) fraction of solid, b) fraction of each solid phase and c) heat evolution latent and total

TABLE 4

ANOVA for Quadratic Mixture model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1656759.84	5	331351.969	23.667	7.9E-06
Linear Mixture	1251535.09	2	625767.547	44.695	2.75E-06
AB	117050.63	1	117050.625	8.360	0.0135
AC	95323.69	1	95323.693	6.808	0.0228
BC	107224.59	1	107224.590	7.658	0.0170
Residual	168008.94	12	14000.745		
Cor Total	1824768.78	17			

v.9.0.6.2, experimental value given in TABLE 3 and Surface Methodology – RSM [28-32] mathematical model for calculation of hardness of Cu-Ge-In alloys was developed. Statistics of selected "Quadratic Mixture model" is given in TABLE 4.

The F-value of the Model is 23.67. Model statistics have good values, which confirms the justification of the choice of the selected mathematical model (TABLE 5).

The final equation of the predictive model in terms of real components is (1):

$$HB(MN/m^2) = 988.57589 * (Cu) + 1005.59551 * (Ge) + 4.70156 * (In) - 1385.51524 * (Cu) * (Ge) - 1250.33062 * (Cu) * (In) - 1326.08583 * (Ge) * (In) \quad (1)$$

TABLE 5

Computational values of statistics for the evaluation of a mathematical model

Std. Dev.	118.325	R-Squared	0.908
Mean	369.146	Adj R-Squared	0.870
C.V. %	32.054	Pred R-Squared	0.708
PRESS	533590.022	Adeq Precision	14.966

The diagnosis of the statistical properties of the assumed model found that the distribution of residuals are normal. After the applied Box-Cox procedure, the value of λ is 1.0, the optimum value of λ is 0.52 and the 95% confidence interval for λ (Low C.I. = 0.02, High C.I. = 1.05) contains the value 1.0, thus proving the justification of the model transformation (Fig. 7).

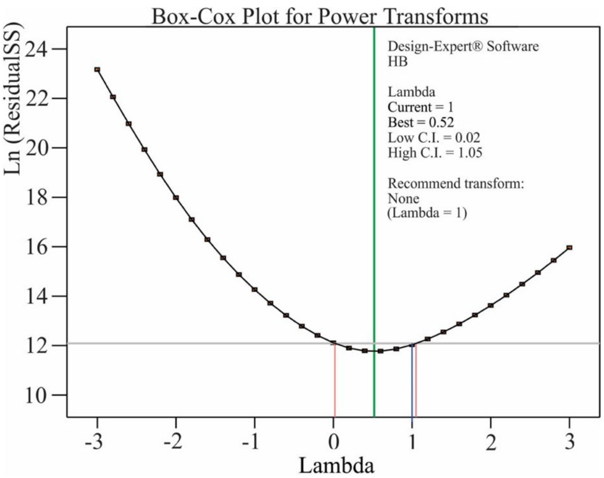

Fig. 7. The Box-Cox plot for power transforms

By using Eq. (1), expected Brinell hardness value are graphically presented in Fig. 8.

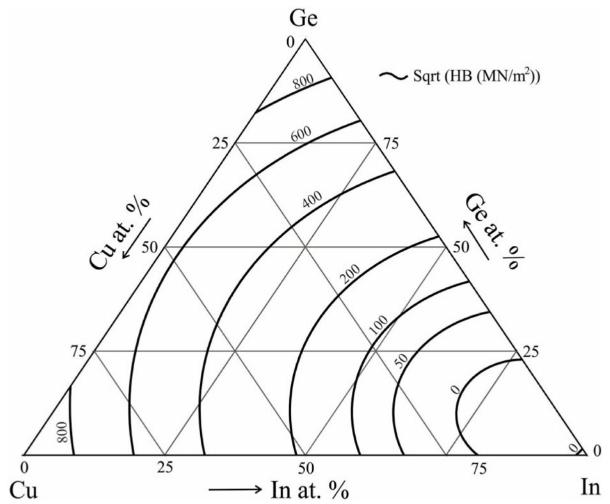

Fig. 8. Calculated Brinell hardness of the ternary Cu-Ge-In system by using proposed mathematical model, Eq. (1)

3.1.3. Electrical properties

Samples as presented in TABLE 2 are used for electrical conductivity measurement. Measurement was performed in three different point and results are summarized in TABLE 6. Based on three points measurement mean value of electrical conductivity were calculated and presented in last columns, together with literature values of pure elements [33].

TABLE 6

Phase fraction, experimental electrical conductivity values of three measurement and mean value of tested ternary Cu-Ge-In samples

N.	Calculated fraction of phases	Value (MS/m)			Mean value (MS/m)
		1	2	3	
B1	50% (In) 50% (Ge)	3.832	3.433	3.598	3.621
1	23.64 % (In) 40% (Ge) 36.36% $Cu_{11}In_9$	3.196	3.177	3.243	3.205
2	16.67% η" 30% (Ge) 53.33% $Cu_{11}In_9$	3.646	3.785	3.562	3.664
3	32.59% η 55.56% η" 11.85% (Ge)	4.646	4.785	4.562	4.664
4	22.67% η 33.33% δ 44% ξ	7.865	7.543	7.986	7.798
Cu	100% (Cu)				59 [33]
B2	50% (In) 50% (Cu)	9.876	9.812	9.325	9.671
5	7.27% (In) 20% (Ge) 72.73% $Cu_{11}In_9$	4.234	4.296	4.513	4.347
6	5.45% (In) 40% (Ge) 54.55% $Cu_{11}In_9$	1.234	1.432	1.289	1.318
7	3.64% (In) 60% (Ge) 36.36% $Cu_{11}In_9$	0.878	0.876	0.812	0.855
8	1.82% (In) 80% (Ge) 18.18% $Cu_{11}In_9$	0.234	0.765	0.341	0.446
Ge	100% (Ge)				0.002 [33]
B3	50% (Cu) 50% (Ge)	2.342	2.351	2.389	2.360
9	5.93% η 55.55% η" 38.52% (Ge)	1.345	1.378	1.331	1.351
10	15.45% (In) 30% (Ge) 54.55% $Cu_{11}In_9$	0.987	0.329	0.787	0.701
11	43.64% (In) 20% (Ge) 36.36% $Cu_{11}In_9$	2.467	2.487	2.422	2.458
12	71.82% (In) 10% (Ge) 18.18% $Cu_{11}In_9$	3.987	4.023	3.998	4.002
In	100% (In)				12 [33]

Results shows that a sample 4, have best electrical conductivity. For good electrical conductivity is responsable microstructure of sample 4. In sample 4, dominant phase is ξ with 44%, then δ phase with 33.33% and η phase with 22.67%. Beside microstructure high value of electrical conductivity is linked with high amount of copper in sample 4.

On Figs. 9 and 10 few important diagrams of Scheil and Lever simulations of sample 4 were calculated. Calculated diagrams were fraction of solid, fraction of each solid phase and heat evolution latent and total by using Pandat software.

For better presentation of results given in TABLE 6, Fig. 11 has been ploted.

Same procedure as applied for calculation of mathematical model for hardness is applied for modeling of electrical conductivity. Selected mathematical model is "Quadratic Mixture model" transformed using the "Natural Log" function. ANOVA analysis (TABLE 7) confirmed the adequacy of the transformed model.

TABLE 7

ANOVA for Reduced Quadratic Mixture model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	7.68311	4	1.92078	31.55853	1.3954E-06
Linear Mixture	5.29056	2	2.64528	43.46219	1.7489E-06
AB	1.10524	1	1.10524	18.15912	0.00093
AC	1.00433	1	1.00433	16.50126	0.00135
Residual	0.79123	13	0.06086		
Cor Total	8.47434	17			

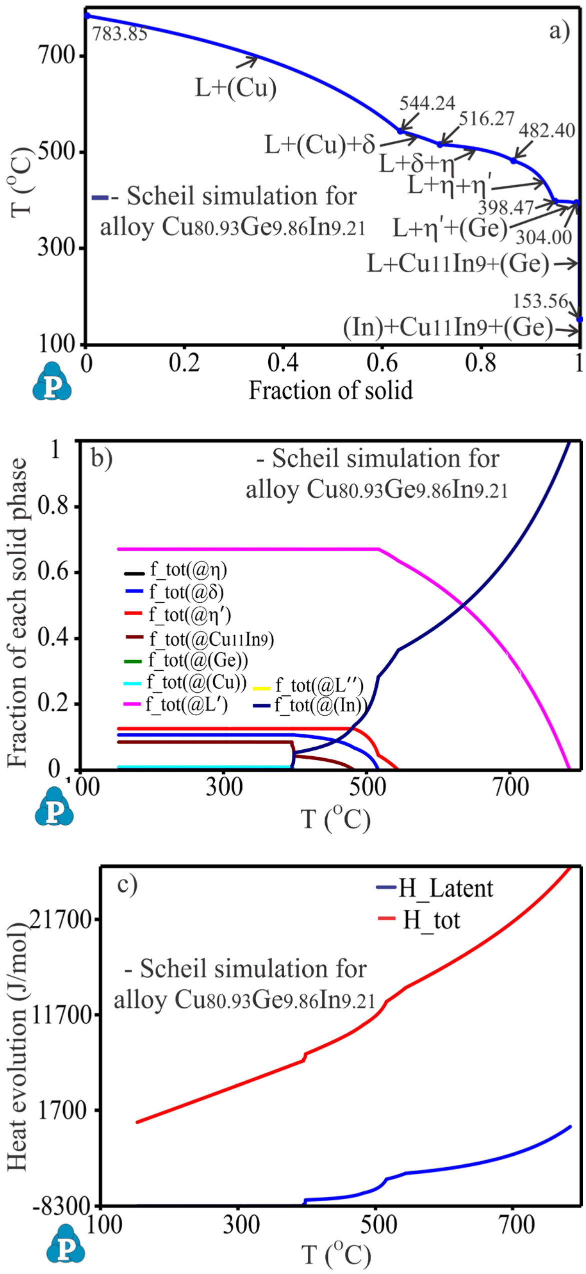

Fig. 9. Scheil simulation for sample 4, alloy a) fraction of solid, b) fraction of each solid phase and c) heat evolution latent and total

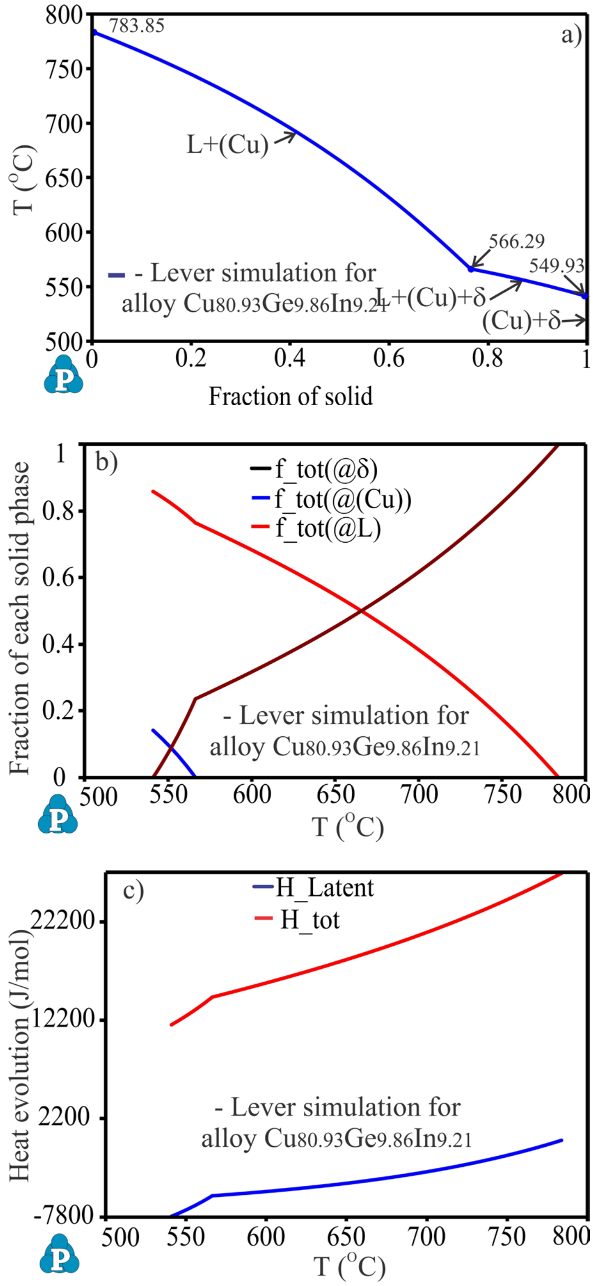

Fig. 10. Lever simulation for sample 4, alloy $Cu_{80.93}Ge_{9.86}In_{9.21}$ a) fraction of solid, b) fraction of each solid phase and c) heat evolution latent and total

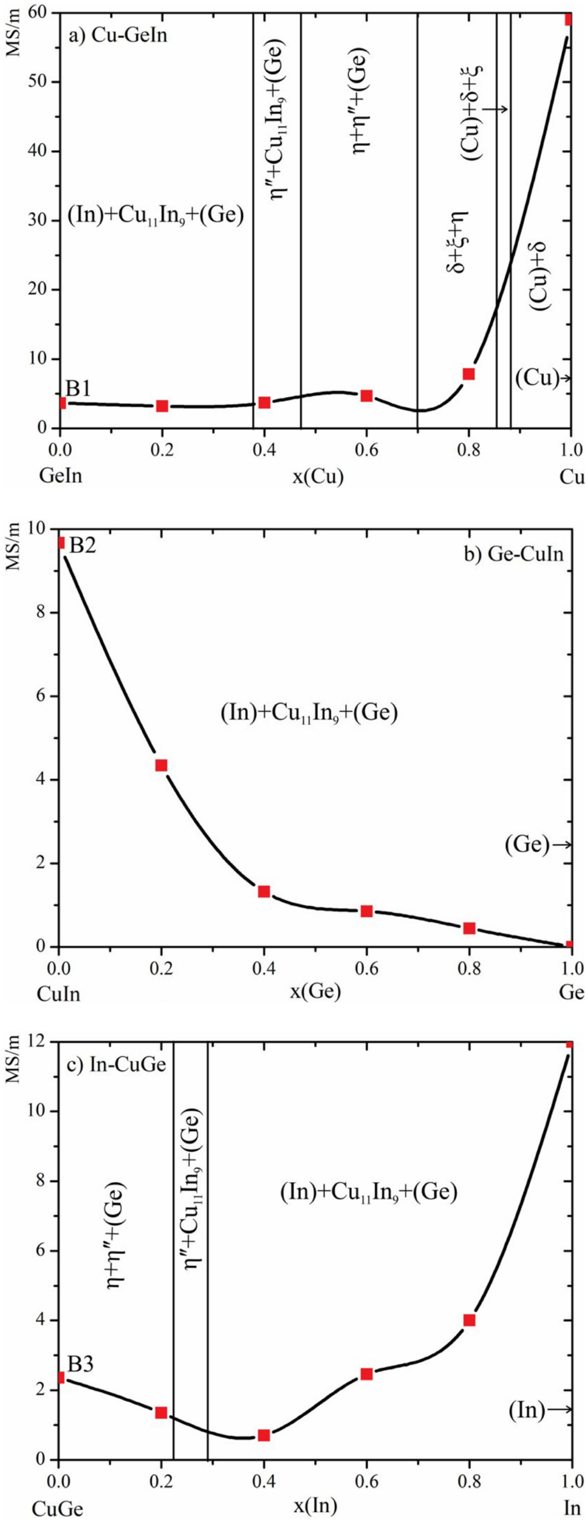

Fig. 11. Experimentally determined values of electrical conductivity for: a) samples 1 to 4, b) samples 5 to 8 and c) samples 9 to 12

TABLE 8

Computational values of statistics for the evaluation of a mathematical model

Std. Dev.	0.24671	R-Squared	0.90663
Mean	1.92488	Adj R-Squared	0.87790
C.V. %	12.81667	Pred R-Squared	0.72410
PRESS	2.33804	Adeq Precision	21.34419

The F-value of the Model is 31.56 and it implies that the model is significant. Statistics have good values which confirm the justification of the choice of the adopted mathematical model (TABLE 8).

The final Eq. (2) of the predictive model in terms of actual components is:

$$\text{Ln(EP + 3.00)} = 3.930479473 * \text{(Cu)} + 1.155188289 * \text{(Ge)} + 2.549564358 * \text{(In)} - 4.233555034 * \text{(Cu)} * \text{(Ge)} - 4.03567672 * \text{(Cu)} * \text{(In)} \quad (2)$$

The diagnosis of the statistical properties of the assumed model found that the distribution of residuals are normal. After the applied Box-Cox procedure, the value of λ is 0.0, the optimum value of λ is –0.36 and the 95% confidence interval for λ (Low C.I. = –1.02, High C.I. = 0.09) contains the value 0.0, thus proving the justification of the model transformation. (Fig. 12).

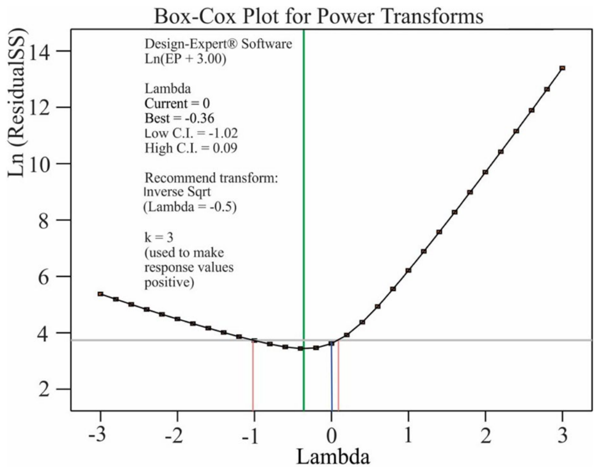

Fig. 12. The Box-Cox plot for power transforms.

Iso-lines contour plot for electrical conductivity of Cu-Ge-In alloys defined by equation (2) is shown in Fig. 13.

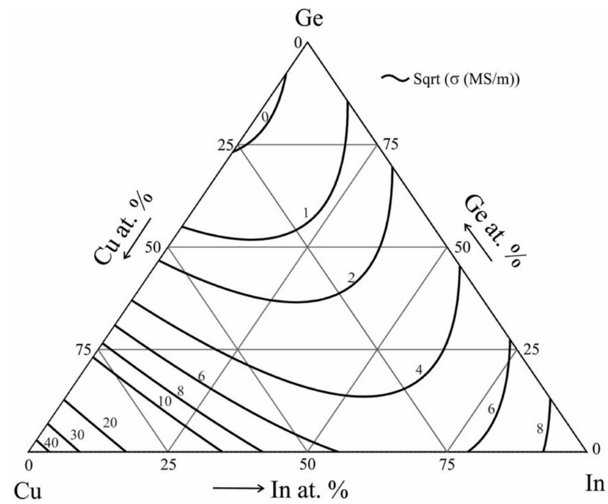

Fig. 13. Calculated electrical conductivity of the ternary Cu-Ge-In system by using proposed mathematical model, Eq. (2)

4. Conclusion

In this paper, coper and germanium based alloys were selected for different experimental test. Due to the wide application of Cu-Ge-X alloys it is important to test those alloys. Selected alloys were chosen to be from three different vertical sections. Samples from 1 to 4 are from vertical section Cu-GeIn, samples from 5 to 8 are from vertical section Ge-CuIn, while samples 9 to 12 are from In-GeCu section. Results of XRD and EDS tests were compared with isothermal sections at 25 ° C and good overall agreement has been reached. Hardness and electrical conductivity test were performed. Best harness and electrical conductivity show to have sample 4, $Cu_{80.93}Ge_{9.86}In_{9.21}$. Detected hardness for sample 4 is 811.5, 818.92 and 816.18 MN/m^2 (mean value 815.53 MN/m^2). Detected electrical conductivity of sample 4 is 7.865, 7.543 and 7.986 MS/m, while mean value is 7.798 MS/m. Good properties of sample 4, is linked with microstructure of sample 4. In this sample three phases are detected η, δ and ξ. This microstructure has 22.67% of the η phase, 33.33% of the δ phase and 44% of the ξ phase. Those properties are mathematically modeled and by using proposed equation 1 and 2 properties were calculated along all composition ranges.

Due to the good electrical properties of alloy $Cu_{80.93}Ge_{9.86}$-$In_{9.21}$ possible application this alloy can found in electrical industry. In addition to the special application of the alloys, the important information provided in this paper is of interest for future investigations of these alloys. Future work can be extended to a higher order system without treating the experiment of this system only by increasing the alloys up to the quaternary. Practical use of presented results in paper is as a basis for tests of high-order systems. For test of high-order system it is necessary to have information of low-order systems such as binary and ternary. Those information are important due to the fact that high order system usually have real application.

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REFERENCES

[1] M. Milosavljevic, M. Premovic, D. Minic, D. Manasijevic, A. Djordjevic, M. Tomovic, Thermodynamic Description of the Cu-Ge-In System: Exsperiment and modeling. J. Phase. Equilibria. Diffus. **42**, 851-863 (2021).
DOI: https://doi.org/10.1007/s11669-021-00930-9

[2] M. Milosavljević, A. Djordjević, D. Minić, M. Zečević, M. Kolarević, Mechanical and electrical properties of the ternary Cu-Ge-Pb and Cu-Ge-In alloys. IRASA International Scientific Conference Science, Education, Technology And Innovation, SETI IV 2022, book of proceedings, 123-133.

[3] D. Orac, M. Laubertova, J. Piroskova, D. Klein, R. Bures, J. Klimko, Characterization of dusts from secondary copper production. J. Min. Metall. B. **56** (2) B, 221-228 (2020).
DOI: https://doi.org/10.2298/jmmb190820011O

[4] B. Dong, X. Cai, S. Lin, X. Li, C. Fan, C. Yang, H. Sun, Wire arc additive manufacturing of Al-Zn-Mg-Cu alloy: Microstructures and mechanical properties. Addit. Manuf. **36**, 101447 (2020).
DOI: https://doi.org/10.1016/j.addma.2020.101447

[5] A. Kamegawa, T. Kuriiwa, M. Okada, Effects of dehydrogenation heat-treatment on electrical–mechanical properties for hydrogenated Cu–3 mass%T i alloys. J. Alloys Compd. **566**, 1-4 (2013).
DOI: https://doi.org/10.1016/j.jallcom.2013.02.121

[6] S. Adachi, Properties of Semiconductor Alloys: Group-IV, III-V and II-VI, Semiconductors, Wiley, Hoboken (2009).

[7] A. Rockett, The Materials Science of Semiconductors, Springer, Berlin (2008).

[8] G.W. Burr, B.N. Kurdi, J.C. Scott, C.H. Lam, K. Gopalakrishnan, R.S. Shenoy, Overview of candidate device technologies for storage-class memory. IBM J. Res. Dev. **52** (4-5), 449-464 (2008).
DOI: https://doi.org/10.1147/rd.524.0449

[9] M. Milosavljevic, M. Premovic, D. Minic, D. Manasijevic, A. Todic, M. Tomovic, Thermodynamic description of the Cu-Ge-Pb system: Experiment and modeling. Calphad. **72**, 102216 (2021).
DOI: https://doi.org/10.1016/j.calphad.2020.102216

[10] H. Kim, J.H. Ahn, S.Z. Han, J. Jo, H. Baik, M. Kim, H.N. Han, Microstructural characterization of cold-drawn Cu-Ni-Si alloy having high strength and high conductivity. J. Alloys Compd. **832**, 155059 (2020).
DOI: https://doi.org/10.1016/j.jallcom.2020.155059

[11] Y. Cao, S.Z. Han, E.A. Choi, J.H. Ahn, X. Mi, S. Lee, H. Shin, S. Kim, J. Lee, Effect of inclusion on strength and conductivity of Cu-Ni-Si alloys with discontinuous precipitation. J. Alloys Compd. **843**, 156006 (2020).
DOI: https://doi.org/10.1016/j.jallcom.2020.156006

[12] J. Li, G. Huang, X. Mi, L. Peng, H. Xie, Y. Kang, Microstructure evolution and properties of a quaternary Cu–Ni–Co–Si alloy with high strength and conductivity. Mater. Sci. Eng. A. **766**, 138390 (2019).
DOI: https://doi.org/10.1016/j.msea.2019.138390

[13] G. Kim, J. Park, S.J. Lee, H.S. Kim, Microstructure and Hardness of Cu-22Sn-xC Alloys Fabricated by Powder Metallurgy. Arch. Metall. Mater. **68**, 1, 71-75 (2023).
DOI: https://doi.org/10.24425/amm.2023.141474

[14] K. Wojtaszek, F. Cebula, B. Partyka, P. Deszcz, G. Włoch, R.P. Socha, K. Woźny, P. Żabiński, M. Wojnicki, Electrochemical Method of Copper Powder Synthesis on Rotating Electrode in the Presence of Surfactants. Arch. Metall. Mater. **68**, 1, 375-386 (2023).
DOI: https://doi.org/10.24425/amm.2023.141514

[15] A. Al Aboushi, S. Al-Qawabah, N. Abu Shaban, A.E. Al-Rawajfeh, Mechanical Properties, Machinability and Corrosion Resistance of Zamak5 Alloyed by Copper. Arch. Metall. Mater. **68**, 4, 1391-1399 (2023).
DOI: https://doi.org/10.24425/amm.2023.146205

[16] S.K. Halder, G. Sen, An X-ray determination of the thermal expansion of silver and copper-base alloys at high temperature. II. Cu–Ga. Acta Cryst. A. **31**, 158-159 (1975).
DOI: https://doi.org/10.1107/S0021889888006557

[17] A.S. Cooper, Precise lattice constants of germanium, aluminum, gallium arsenide, uranium, sulphur, quartz and sapphire. Acta Cryst. A. **15**, 578-582 (1962).
DOI: https://doi.org/10.1107/S0365110X62001474

[18] N. Ridley, Densities of Some Indium Solid Solutions. J. Less. Common. Met. **8** (5), 354-357 (1965).
DOI: https://doi.org/1016/0022-5088(65)90071-8

[19] K. Schubert, G. Brandauer, ZumAufbau des Systems Kupfer-Germanium. Z. Met. **43**, 262-268 (1952).

[20] V.M. Glasov, A.Y. Potemkin, Interaction between copper and antimony in a solid solution based on germanium with the formation of a charged complex. Semiconductors. **34** (5), 495-501 (2000).
DOI: https://doi.org/10.1134/1.1188014

[21] K. Schubert, H. Breimer, W. Burkhardt, E. Gunzel, R. Haufler, H.L. Lukas, H. Vetter, J. Wegst, M. Wilkens, Einige strukturelle Ergebnisse an metallischen Phasen II. Naturwissenschaften. **44** (7), 229-230 (1957).
DOI: https://doi.org/10.1007/BF00595784

[22] J. Lenz, K. Schubert, Uebereinige Leerstellen- und Stapelvarianten der Beta-Messing Struktur familie. Z. Met. **62**, 810-816 (1971).

[23] G.C. Che, M. Ellner, Powder Crystal Data for the High-Temperature Phases Cu4In, Cu9In4(h) and Cu2In(h). Powder Diffraction **7** (2), 107-108(1992).
DOI: https://doi.org/10.1017/S0885715600018340

[24] S. Lidin, L. Stenberg, M. Elding-Pontén, The B8 type structure of Cu7In3. J. Alloys Compd. **255** (12), 221-226 (1997).

[25] S. R. de Debiaggi, G. F. Cabeza, C. D. Toro, A. M. Monti, S. Sommadossi, A. Fernández Guillermet, Ab initio study of the structural, thermodynamic and electronic properties of the Cu10In7 intermetallic phase. J. Alloys Compd. **509** (7), 3238-3245 (2011).

[26] T. Rajasekharan, K. Schubert, Kristallstruktur von Cu11-In9. Zeitschrift für Metallkunde **72**, 275-278 (1981).

[27] http://www.webelements.com/periodicity/hardness_brinell/ access 25.12.2018

[28] M.J. Anderson, P.J. Whitcomb, RSM Simplified, Optimizing Processes Using Response Surface Methods for Design of Experiments. Second Edition, CRC Press,Taylot & Francis Group (2017).

[29] G.E.P. Box, N.R. Draper, Response Surfaces, Mixtures, and Ridge Analyses, Second Edition, Wiley (2007).

[30] Stat-Ease, Handbook for Experimenters, Version 11.00, Stat-Ease, Inc. (2018).

[31] D.C. Montgomery, Design and Analysis of Experiments, Ninth Edition, Wiley (2017).

[32] R.H. Myers, D.C. Mongomery, C.M. Anderson-Cook, Response Surface Methodology, Process and Product Optimization Using Designed Experiments, Fourth Edition, Wiley (2016).

[33] http://periodictable.com/Properties/A/ElectricalConductivity.an.html, access 16.01.2022.