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Improving the structure, tensile strength and hardness of molybdenum-doped copper-silicon alloy system

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Abstract: **Cu-Be alloys are known for their outstanding strength, hardness, and electrical conductivity. They are often used in applications where high performance is required, such as aerospace, electronics, and telecommunications. One significant drawback of Cu-Be alloys is that beryllium is toxic and poses health risks, especially during the manufacturing and machining processes. This has led to concerns about worker safety and environmental impact. In this study, novel Cu-Si-Mo ternary alloys composition with improved tensile strength, ductility, and hardness are produced. The Cu-3Si-xMo (x: 0.1-5 wt%) alloys were fabricated via stir-casting technique. The surface morphologies of the Cu-Si and Cu-Si-Mo alloys were investigated and linked with the mechanical properties using optical metallurgical microscope (OM). Results of the study indicated that tensile strength, ductility, and hardness of the parent alloy improved significantly, recording maximum values of 130 MPa, 18.4%, and 192 BHN, respectively. Alloy with composition; Cu-3Si-1.5Mo gave the best mechanical properties, owing to increased solid solution strengthening, modification, and refinement of the dendritic grains by molybdenum addition.**

Keywords: **Strength, hardness; morphology; Cu-Si-Mo alloy; composition.**

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1. INTRODUCTION

Copper-based alloys are essential materials with a wide range of properties that make them indispensable in various industries. Copper is well-known for its electrical and thermal conductivity, corrosion resistance, and ductility, however, ongoing research and development efforts are exploring alternative alloys to address specific limitations and drive further advancements in copper-based materials (Xie et al., 2003; Qing et al., 2011; Yu et al., 2011; Jeong et al., 2009). Copper is renowned for its excellent electrical conductivity, making it an ideal choice for electrical and electronic applications. It's used extensively in wiring, cables, and electrical components because it allows for efficient transmission of electrical power and signals. Copper also possesses outstanding thermal conductivity. This property makes it suitable for applications where efficient heat transfer is essential, such as heat exchangers, radiators, and condenser tubes. Copper's ability to conduct heat efficiently ensures effective heat dissipation in various industrial processes and systems. Copper and its alloys are highly resistant to corrosion, which is a critical factor in applications where exposure to moisture or corrosive environments is a concern(Yu et al., 2011; Jeong et al., 2009). This corrosion resistance makes copper alloys suitable for use in water pipes, automotive components, and railway infrastructure, where durability is essential. Copper is highly ductile, meaning it can be easily shaped and formed into various configurations. This property is invaluable for industries like automotive, construction, and plumbing, where copper components need to be fabricated into specific shapes and sizes to meet design requirements.

Copper-Beryllium (Cu-Be) alloys are known for their exceptional combination of high strength and electrical conductivity. However, they do have limitations, such as toxicity and cost. These drawbacks have led to the exploration of alternative alloys like Cu-Ni-Si, Cu-Si, and Cu-Ti-Si, which aim to maintain similar mechanical properties while addressing the issues associated with Cu-Be alloys(Nnakwo, 2019; Nnakwo et al., 2017a,b; 2019a,b; 2020, 2021, 2022;Nnakwo and Nnuka, 2018; Cheng et al., 2014; Qing et al., 2011; Qian et al., 2010; Gholami et al., 2017b; Cheng et al., 2014; Wang et al., 2014).The field of copper-based alloys is continually evolving, with ongoing research and development efforts focused on improving existing materials and developing new alloys. This research aims to enhance the properties of copper-based materials, reduce toxicity concerns, and optimize cost-effectiveness. Such innovations can lead to the development of alloys better suited to specific applications and industries.

The high strength and electrical conductivity of Cu-Ni-Si alloyshave been reported to be achieved through various processing techniques such as alloying, thermo-mechanical treatments, and precipitation hardening (Gholami et al., 2017a; Jia et a., 2012; Xie et al., 2009;Lei et al., 2017;Qing et al., 2011;Qian et al., 2010;Gholami et al., 2017b;Cheng et al., 2014; Wang et al., 2014). These alloys exhibit excellent mechanical and electrical properties due to the presence of specific phases, including β1-Ni_3Si, α-Cu (Ni,Si), γ′-Ni_3Al, β-Ni_3Si, and δ-Ni_2Si, as reported in several studies (Qian et al. 2017; Suzuki et al. 2006; Wang et al. 2016; Srivastava et al. 2004; Li et al. 2017; Pan et al., 2007; Li et al., 2009; Lei et al., 2013a; Lei et al., 2013b).However, it is noted that the ductility of these alloys is low, which could limit their application in situations where impact resistance is crucial. To address this limitation, the study aims to improve the tensile strength, ductility, and hardness of Cu-Si based alloys by introducing molybdenum. The effectiveness of molybdenum as an alloying element and its impact on the properties of Cu-Si-based alloys would depend on the alloy's composition, processing techniques, and the specific phases that form within the material. The study aims to investigate these aspects to tailor the alloy's properties for applications that require a combination of high strength, ductility, and hardness

2. EXPERIMENTAL PROCEDURE

Analytical grade copper wire, silicon powder, and molybdenum powder with different percentage purities (98.9%, 95.9%, and 99.7%) were used as starting materials for this experimental study.The alloys were produced by melting the materials together using a bailout crucible furnace. The molten alloys were cast into iron molds with specific dimensions of 16 mm diameter and 250 mm length. The alloys were allowed to cool inside the molds until they reached room temperature. Tensile strength samples were milled to specific dimensions: 120mm total length, 50mm gauge length, and 8mm gauge diameter. Hardness samples were milled to 25 mm length and 15 mm diameter. The surfaces of the samples were ground and polished thoroughly to ensure a consistent surface finish.

Tensile strength tests were conducted according to British standards: BS EN ISO 6892-1:2016. Hardness tests were carried out following BS EN ISO 6505-1:2014. Tensile strength tests were performed using a 100kN capacity automated JPL tensile strength tester (Model: 130812). Hardness tests were conducted using a Brinell hardness tester (Model: DHT-6).Prior to microstructural analysis, the surfaces of the alloy samples were prepared through several steps: grinding with emery paper of different grit sizes, polishing with pure aluminum powder, and etching in a mixture of iron III chloride, HCl, and water.

3. RESULTS AND DISCUSSION

Figs. 1-3 depict the ultimate tensile strength, percentage elongation, and hardness of Cu-3Si binary alloys doped with different concentrations of molybdenum. It is noted in Figs.1-3 that addition of molybdenum resulted in a significant increase in the ultimate tensile strength, percentage elongation, and hardness of Cu-3Si binary alloys. As the concentration of molybdenum increased, the percentage elongation decreased. This means that the materials became less ductile as more molybdenum was added.Figs. 2 and 3 showed that both hardness and ultimate tensile strength values increased with increasing concentrations of molybdenum up to 1.5wt%. This indicates that the alloys became harder and stronger with the addition of molybdenum.The maximum ultimate tensile strength was obtained at 1.5wt%Mo, with a value of 130MPa.The maximum hardness was also achieved at 1.5wt%Mo, with a value of 192 BHN.These improvements in mechanical properties can be attributed to two factors: increased Solid Solution Region: As molybdenum was added, it formed a solid solution with copper and silicon, which enhanced mechanical properties.The addition of molybdenum led to the formation of finer grains in the alloy, which can also contribute to improved mechanical properties. Beyond 1.5wt%Mo, both ultimate tensile strength and hardness started to decline. This decline can be attributed to the coarsening of grains at higher molybdenumcontents (specifically at 5wt%Mo).Coarser grains led to a decrease in mechanical properties as they are less resistant to deformation and fracture.

Fig. 4 shows the microstructure analysis of the developed Cu-3Si and Cu-3Si-xMo alloys. In Fig. 4a, the microstructure analysis shows that the developed Cu-3Si alloy contains evenly dispersed dendritic grains within the copper matrix.These dendritic grains are identified as primary silicon and Cu3Si intermetallic compounds.Figs. 4b, 4c, and 4d represent optical microscope (OM) images of Cu-3Si alloys with varying amounts of Mo (Cu-3Si-0.2Mo, Cu-3Si-1.5Mo, and Cu-3Si-5Mo, respectively).These images reveal that the addition of Mo led to the modification and refinement of the dendritic grains compared to the parent Cu-3Si alloy (Fig. 4a). This refinement resulted in an increased number of grain boundaries and dislocation density within the alloys.The changes observed in the microstructure, such as grain refinement and increased dislocation density, are correlated with an increase in the tensile strength and hardness of the alloy.This suggests that the modified microstructure due to the addition of Mo contributed to improved mechanical properties. The Cu-3Si-5Mo image reveals coarse grains within the copper matrix.The presence of coarse grains is associated with a decrease in the tensile strength and hardness of the alloy, as shown in Figs. 2 and 3.

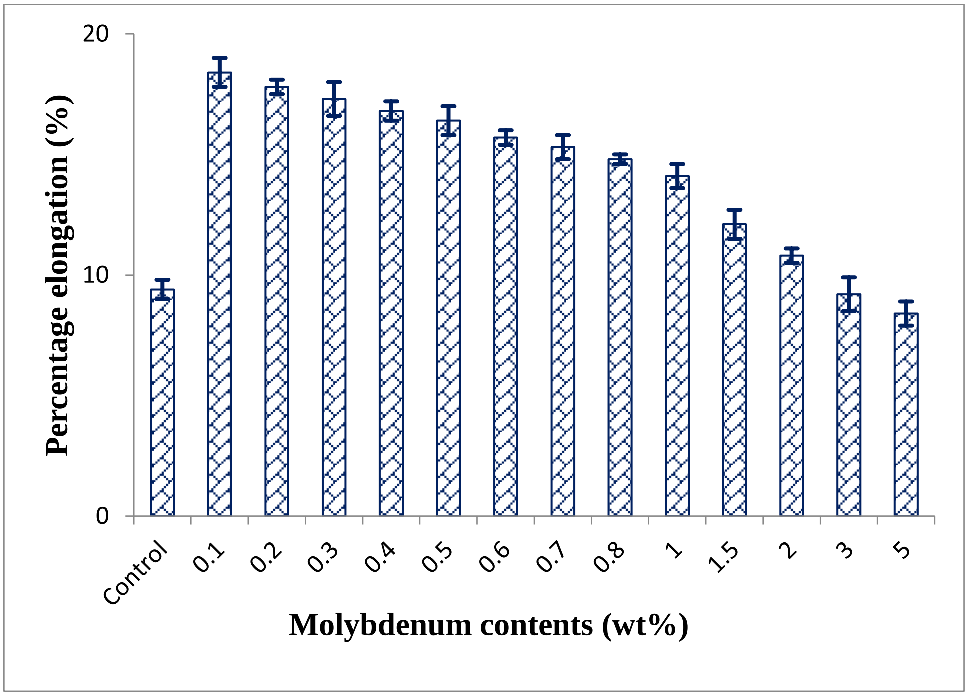

Fig. 1: Percentage elongation of Cu-3Si-xMo ternary alloys

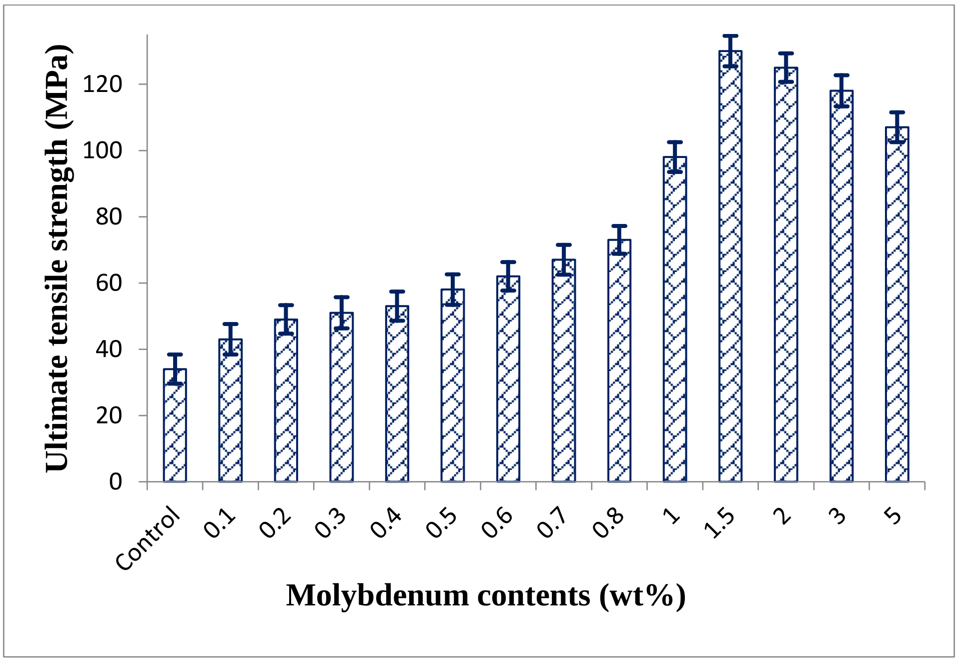

Fig. 2: Ultimate tensile strength of Cu-3Si-xMo ternary alloys

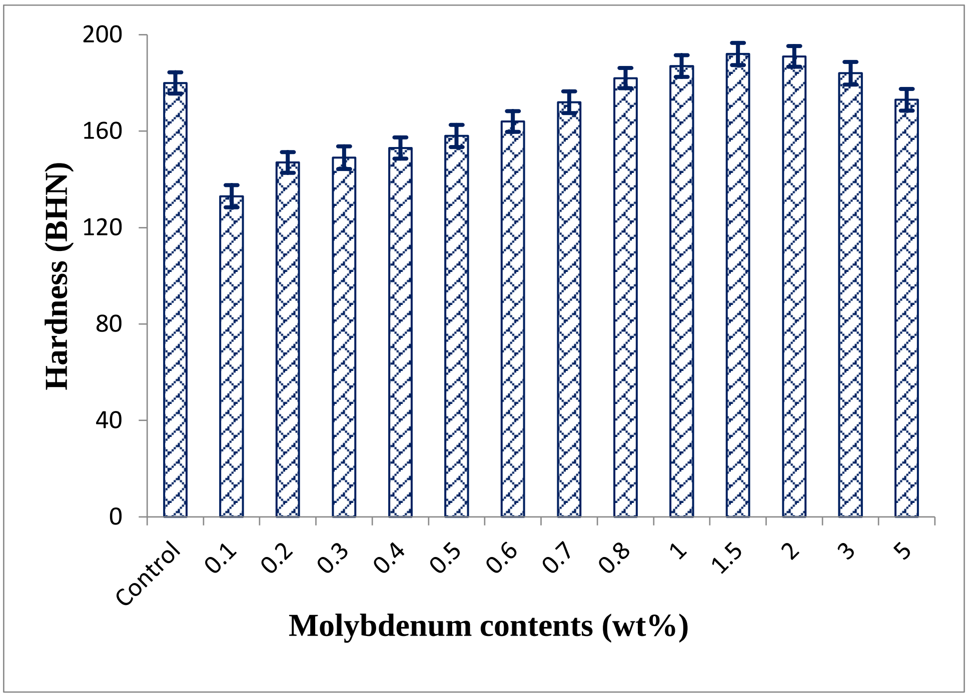

Fig. 3: Hardness of Cu-3Si-xMo ternary alloys

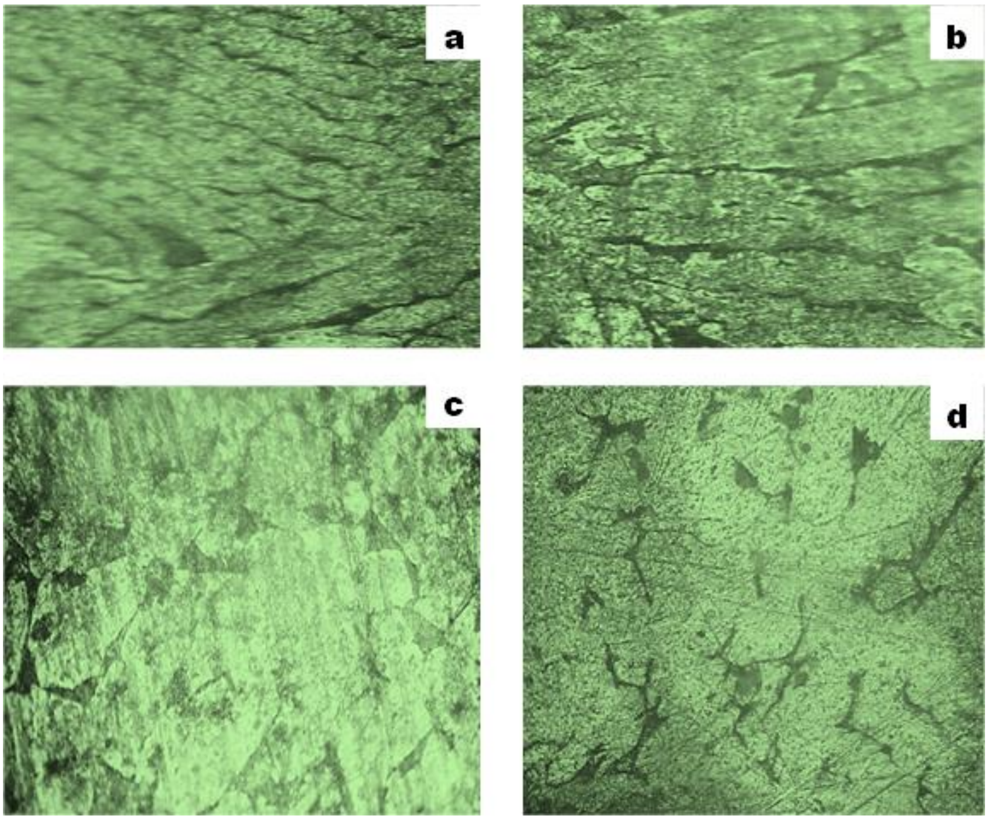

Fig. 4: OM microstructures of (a) Cu-3Si (b) Cu-3Si-0.2Mo (c) Cu-3Si-1.5Mo (d) Cu-3Si-5Mo alloys

4. CONCLUSIONS

A novel Cu-Si-Mo ternary alloys composition with improved tensile strength, ductility, and hardness has been produced. The Cu-3Si-xMo (x: 0.1-5 wt%) alloys were fabricated via stir-casting technique. Results of the study have shown that addition of molybdenum to Cu-3Si binary alloys had a significant impact on their mechanical properties, leading to increased strength and hardness up to a certain concentration (1.5wt%Al), beyond which the properties started to deteriorate due to grain coarsening. These findings are crucial for understanding the behavior of these alloys and optimizing their composition for specific applications. The tensile strength, ductility, and hardness of the parent alloy recorded maximum values of 130 MPa, 18.4%, and 192 BHN, respectively. Alloy with composition; Cu-3Si-1.5Mo gave the best mechanical properties, owing to increased solid solution strengthening, modification, and refinement of the dendritic grains by molybdenum addition. The percentage elongation showed a decreasing trend with increasing concentration of molybdenum.

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REFERENCES

[1] Cheng, J.Y., Tang, B.B., Yu, F.X., Shen, B., 2014. Evaluation of nanoscaled precipitates in a Cu–Ni–Si–Cr alloy during ageing. Journal of Alloys and Compounds.614,189–195.

[2] Gholami, M., Vasely, J., Altenberger, I., Kuhn, H. A., Wollmann, M., Janecek, M., Wagner, L., 2017a. Influence of grain size and precipitation hardening on high cycle fatigue performance of CuNiSi alloys. Materials Science and Engineering A. 684, 524-533.

[3] Gholami, M., Vasely, J., Altenberger, I., Kuhn, H. A., Wollmann, M., Janecek, M., Wagner, L., 2017b.Effect of microstructure on mechanical properties of CuNiSi alloys.Journal of Alloys and Compounds. 696, 201-212.

[4] Huang F, Jusheng M, Honglong N, YuWen C, Zhiting G., 2003. Precipitation in Cu–Ni–Si–Zn alloy for lead frame.Materials Letters. 57, 2135-2139.

[5] Jeong, E. H., Han, S. Z., Goto, M. and Kim, S. S., 2009.Materials Science and Engineering A. 520, 66.

[6] Jia, L., Xie, H., Lu, Z. L., Wang, X., Wang, S. M., 2012. Netted structure of grain boundary phases and its influence on electrical conductivity of Cu–Ni–Si system alloys. Materials Science and Technology. 28 (2), 243-248.

[7] Lei, Q., Li, Z., Dai, C., Wang, J., Chen, X., Xie, J. M., Yang, W. W., Chen, D. L., 2013a.Effect of aluminium on microstructure and property of Cu–Ni–Si alloys. Materials Science and Engineering A. 572, 65-74.

[8] Lei, Q., Li, Z., Xiao, T., Pang, Y., Xiang, Q. Z., Qiu, W. T., Xiao, Z., 2013b.A new ultrahigh strength Cu-Ni-Si alloy, Intermetallics. 42, 77-84.

[9] Lei, Q., Xiao, Z., Hu, W., Derby, B., Li, Z., 2017. Phase transformation behaviors and properties of a high strength Cu-Ni-Si alloy. Materials Science and Engineering A. 697, 37-47.

[10] Li, Z., Pan, Z. Y., Zhao, Y. Y., Xiao, Z., Wang, M. P. P., 2009. Microstructure and properties of high-conductivity, super-high-strength Cu-8.0Ni-1.8Si-0.6Sn-0.15Mg alloy. Journal of Materials Research Society.24(6), 2123-2129.

[11] Li, D., Wang, Q., Jiang, B., Li, X., Zhou, W., Dong, C., Wang, H., Chen, Q., 2017.Minor-alloyed Cu-Ni-Si alloys with high hardness and electric conductivity designed by a cluster formula approach. Progress in Natural Science: Materials International. 27, 467–473.

[12] Nnakwo, K. C., Okeke, I.U., Nnuka, E.E., 2017a. Structural modification and mechanical properties of Cu-3wt%Si-xwt%Sn alloy. International Journal of Scientific Research in Science, Engineering and Technology. 3, 184-187.

[13] Nnakwo, K. C., Okeke, I.U., Nnuka, E.E., 2017b.Effect of zinc content on the structure and mechanical properties of silicon bronze.International Journal of Scientific Research in Science, Engineering and Technology. 3, 179-183.

[14] Nnakwo, K. C., Nnuka, E. E., 2018. Correlation of the structure, mechanical and physical properties of Cu3wt%Si-xwt%Sn silicon bronze. Journal of Engineering and Applied Sciences. 13, 83-91.

[15] **Nnakwo K. C.**, 2019.Effect of tungsten content on the structure, physical and mechanical properties of silicon bronze (Cu-3wt%Si), *Journal of King Saud University - Science*, 31(4), 844-848.doi: https://doi.org/10.1016/j.jksus.2017.12.002.

[16] Nnakwo, K. C., Mbah, **C. N.,** and Daniel-Mkpume, C. C., 2019a.Investigation of the structural sensitive behavior of Cu-3Si-xMn ternary Alloys.*Journal of King Saud University –Science*, 31(4), 1056-1063.https://doi.org/10.1016/j.jksus.2019.01.001.

[17] Nnakwo, K. C.,Mbah, C. N., and Nnuka, E. E., 2019b. Influence of trace additions of titanium on grain characteristics, conductivity and mechanical properties of copper-silicon-titanium alloys. Heliyon.5(10), e02471.https://doi.org/10.1016/j.heliyon.2019.e02471.

[18] **Nnakwo**, K. C., Mbah, C. N., and Ude, S. N., 2020. Influence of chemical composition on the conductivity and on some mechanical properties of Mg-doped Cu-Si alloy. *Journal of King Saud University–Engineering Science.32 (5),287-292* https://doi.org/10.1016/j.jksues.2019.03.005.

[19] **Nnakwo, K. C.,**Osakwe, F. O., Ugwuanyi, B. C., Oghenekowho, P. A.,Okeke, I. U., &Maduka, E. A., 2021. Grain characteristics, electrical conductivity, and hardness of Zn-doped Cu–3Si alloys system. *SN Applied Sciences*, *3*(11). https://doi.org/10.1007/s42452-021-04784-1.

[20] **Nnakwo,** K. C., Odo, J. U., Eweka, K. O., Okafor, J. S., Ijomah, A. I., Maduka, E. A., and Ugwuanyi, B. C., 2022. Evaluation of the Electrical Conductivity and Mechanical Properties of Cu–3Ti–1.5Ni–0.5Si Quaternary Alloy, *JOM: the journal of the minerals, metals, and materials society*, Vol. 74, (Issue 5); 4174-4180.

[21] Pan, Z. Y., Wang, M. P., Li, Z., 2007. Effect of trace elements on properties of Cu-Ni-Si alloy. Materials Review. 21 (5), 86–89.

[22] Puathawee S, Rojananan S, Rojananan S., 2013. Lead-free Cu-Si-Zn brass with tin addition, Advanced Materials Research. 802, 169-173.

[23] Qian, L., Zhou, L., Zhi-yong P., Ming-pu, W., Zhu, X.,Chang, C., 2010. Dynamics of phase transformation of Cu-Ni-Si alloy with super-high strength and high conductivity during aging. Transactions of Non-ferrous Metals Society of China. 20 (6), 1006-1011.

[24] Qian, L., Zhou, L., Zhou L., Yang G., Xi, P., Benjamin, D., 2017.Microstructure and mechanical properties of a high strength Cu-Ni-Si alloy treated by combined aging processes.Journal of Alloys and Compounds.695, 2413-2423.

[25] Qing, L., Li, Z., Wang, M. P., 2011. Phase transformation behavior in Cu–8.0Ni–1.8Si alloy. Journal of Alloys and Compounds.509(8), 3617.

[26] Srivastava, V. C., Schneider, A., Uhlenwinkel, V.,Ojha, S. N., Bauckhage, K., 2004. Age hardening charaeristics of Cu-2.4Ni-0.6Si alloy. Journal of Materials Processing Technology.147 (2), 174-180.

[27] Suzuki, S., Shibutani, N., Mimura, K., Isshiki, M., Waseda, Y., 2006.Improvement in strength and electrical conductivity of Cu–Ni–Si alloys by aging and cold rolling.Journal of Alloys and Compounds. 417 (1-2), 116–120.

[28] Wang, H., Chen, H., Gu, J., Hsu, C., Wu, C., 2014. Effect of heat treatment processes on the microstructures and properties of powder metallurgy produced Cu-Ni-Si-Cr alloy. Materials Science and Engineering A. 619, 221-227.

[29] Wang, W., Kang, H., Chen, Z., Chen, Z.,Li, R., Yin, G.,Wang, Y., 2016. Effects of Cr and Zr addition on microstructure and properties of Cu-Ni-Si alloys. Materials Science and Engineering A. 673, 378-390.

[30] Xie, S. S, Li, Y. L., Zhu, L., 2003.Progress of study on lead frame copper alloy and its implementation in electronic industry.Rare Metals.27(6), 769.

[31] Xie, H., Jia, L., Lu, Z.(2009). Microstructure and solidification behavior of Cu-Ni-Si alloys. Materials Characterization, 60 (2), 114-118.

[32] Yu, F. X, Cheng, J. Y, Ao, X. W., 2011. Aging characteristic of Cu–0.6Cr– 0.15Zr–0.05 Mg–0.02Si alloy containing trace rare earth yttrium.Rare Metals.30(5), 539.