INVESTIGATION OF NICKEL ALUMINIUM BRONZE (NAB) METALS CAST AND ITS PROPERTIES

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science

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I hereby declare that the work in this thesis is based on my original work except for quotations and citation which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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Dedication

I dedicated this to my wife and my children, my parent and my siblings

My supervisor and those who guided and motived me for completing this study

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ABSTRAK

Terdapat tiga jenis gangsa aluminium iaitu gangsa aluminium binary, gangsa aluminium nikel kompleks dan gangsa aluminium silikon yang bermula daripada penambahan kecil aluminium ke dalam tembaga. Ianya bermula daripada penyelidik terdahulu yang menemui peningkatan kekerasan aloi kuprum tanpa menjejaskan sifat kebolehtempaannya. Menghasilkan aloi NAB boleh membawa kepada penyerapan gas oksigen dan hidrogen sewaktu peringkat pencairan dan mewujudkan kesan kecacatan pada sifat mekanikal dan fizikal aloi NAB. Cabaran lain juga wujud apabila produk mempunyai bentuk yang kompleks yang mengakibatkan kepelbagaian kadar penyejukan semasa pemejalan dan mengakibatkan ketidakseragaman pada struktur mikro. Aloi kuprum yang digunakan dalam kajian ini adalah aloi Nikel Aluminium Gangsa (NAB), yang terdiri daripada beberapa unsur-unsur seperti Cu, Al, Fe, dan Mn. Daripada litaratur yang terdahulu, ubahsuai struktur mikro aloi NAB telah terbukti akan meningkatkan kualiti aloi bagi aplikasi automotif dan marin. Sampel adalah rod penyambung enjin yang dibentuk menerusi acuan menggunakan teknik tuangan pasir. Komposisi telah disediakan mengikut piawaian ASTM B148 UNS95800 dan dicairkan menggunakan relau aruhan induksi sehingga suhu 1100˚C, kemudian dituangkan ke dalam acuan tuangan pasir dengan agen penyahgas sebanyak 1.1%. Sampel memejal pada suhu ambien. Kemudian spesimen dipotong kepada 3 bahagian mengikut ketebalannya. Kajian diteruskan dengan menyiasat sifat, struktur mikro, struktur dendrit, dan kakisan mengunakan perkakasan mikroskop optik, SEM, FESEM, EDS, dan XRD. Berdasarkan dari keputusan, mikrostruktur menunjukkan kuantiti DAS dan SDAS seunit luas menjadi lebih tinggi disebabkan oleh masa pemejalan yang lebih lama. Suhu leburan adalah lebih tinggi apabila ketebalan meningkat disebabkan oleh jumlah tuangan yang lebih tinggi. Saiz dan dimensi mikro struktur juga berubah. Ini akhirnya menghasilkan sifat yang lebih baik, seperti kekerasan yang lebih tinggi dan rintangan kakisan yang baik. Permukaan patah juga mendedahkan butir struktur dendritik dan sempadan ira. Kemudian, spesimen telah direndam dalam air laut dalam kajian rintangan kakisan. Perubahan dalam jisim spesimen, nilai pH, dan TDS air laut yang digunakan telah diukur. Analisis data mendedahkan bahawa spesimen belum terkakis sepenuhnya untuk tempoh rendaman, kerana terdapat sedikit variasi fasa dalam jisim spesimen. Nilai pH dan TDS menunjukkan perubahan, tetapi perubahan ini adalah minimum secara perbandingan. Kesimpulan penyelidikan menunjukkan bahawa kesan penyahgasan pada ketebalan rongga yang bersifat mekanikal NAB pada bahagian yang lebih tebal menahan haba pendam lebih lama dan kadar penyejukkan yang lebih perlahan yang menghasilkan kekerasan mikro yang lebih rendah, menghasilkan saiz ira yang lebih besar, DAS dan SDAS yang lebih besar dan kemungkinan untuk mempunyai kadar kakisan yang lebih tinggi berbanding bahagian yang lebih nipis. Berdasarkan hasil kajian ini, aloi NAB sangat sesuai digunakan dalam aplikasi maritim dengan kadar kakisan yang lebih rendah dan sifat mekanikal yang lebih baik.

ABSTRACT

There are three major types of aluminium bronze which is Binary Aluminium Bronze, complex nickel aluminium bronze and silicon aluminium bronze which start from a small addition of aluminium into copper which started from the discovered previous researcher that resulting an increase of hardness of copper alloy without affecting its malleability. Producing NAB alloy can lead to the absorption of gaseous such as oxygen and nitrogen during solidification stage and create a defect on properties and physical to NAB alloy. Another challenge is also present when a product has a complex shape resulting in a variety of cooling rates during solidification and resulting to non-uniformity of the microstructure of the product. This study inspects the effect of thickness during the metal casting process on the microstructure of copper alloy products toward to its properties, microstructure and corrosion. The copper alloy used in this project is Nickel Aluminium Bronze (NAB) alloy, which consists of elements such as Cu, Al, Fe, and Mn. From the previous literature, adjustment of NAB alloy microstructure has been proven to improve the quality toward to properties in automotive and marine applications. The sample is shaped like a connecting rod and fabricated using the sand casting technique. The composition was prepared according to the ASTM B148 UNS95800 standards and melted using an induction furnace at 1100˚C, then poured into a sand casting mould with a 1.1% degassing agent. The sample solidified at ambient temperatures, and then the specimen from the NAB alloy sample was cut into 3 sections according to its thickness. The study is continued by investigating the properties, microstructure, dendrite structure, and corrosion by optical microscope, SEM, FESEM, EDS, and XRD. Based on the results, the microstructure morphology shows a quantity of DAS and SDAS per unit area becomes higher due to a longer solidification time. Casting cavity's temperature is higher as the thickness increases due to higher casting volume in the melting state. The size and dimension are affected as well. This eventually results in better properties, such as higher hardness and good corrosion resistance. The fracture surface also reveals intergranular fracture between the dendritic structure and grain boundaries. Later, the specimens were immersed in seawater in the corrosion resistance study. Changes in the specimen mass, pH and TDS values of the seawater used were measured. The data analysis revealed that the specimens were not fully corroded for the immersion period, as there were phase variations in the specimen microstructure. The pH and TDS values show changes, but these changes are minimal comparatively. The conclusion of research shown that effect of degassing on different cavity thickness of NAB mechanical properties on thicker which is holding longer latent heat and slower cooling rate that produces part produces lower microhardness, larger grain size, larger DAS and SDAS and possibility to have a higher corrosion rate compared to thinner part. Based on this research, NAB alloy are very suitable to be use in maritime application with its lower corrosion rate and improved mechanical properties.

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REFERENCES

Abdel-Jaber, G. T., Omran, A. M., Khalil, K. A., Fujii, M., Seki, M., & Yoshida, A. (2010). An investigation into solidification and mechanical properties behavior of Al-Si casting alloys. *International Journal of Mechanical and Mechanics Engineering*, *10*(4), 34–41.

Al-Hashem, A., & Riad, W. (2002). The role of microstructure of nickel-aluminium-bronze alloy on its cavitation corrosion behavior in natural seawater. *Materials Characterization*, *48*(1), 37–41. https://doi.org/10.1016/S1044-5803(02)00196-1

Anantapong, J., Uthaisangsuk, V., Suranuntchai, S., & Manonukul, A. (2014a). Effect of hot working on microstructure evolution of as-cast Nickel Aluminum Bronze alloy. *Materials and Design*, *60*, 233–243. https://doi.org/10.1016/j.matdes.2014.03.033

Anantapong, J., Uthaisangsuk, V., Suranuntchai, S., & Manonukul, A. (2014b). Effect of hot working on microstructure evolution of as-cast Nickel Aluminum Bronze alloy. *Materials and Design*, *60*(May 2020), 233–243. https://doi.org/10.1016/j.matdes.2014.03.033

Arm, D., In, S., Cylinder, A., Produced, H., & Mold, G. S. (2003). Alloy cylinder heads produced by gravity semi-permanent mold alloy cylinder heads produced by gravity semi-permanent mold. *Metallurgical Science and Technology*, *21*(1), 1–8.

Askeland, D. R. (1994). The Science and Engineering of Materials. In *European Journal of Engineering Education* (Vol. 19, Issue 3). Cengage Learning. https://doi.org/10.1080/03043799408928327

Baboian, R. (2005) Corrosion Tests and Standards: Application and Interpretation. 2nd Edition, 2005 ASTM Manual Series, West Conshohocken

Bala, K. C., & Khan, R. H. (2013). *Experimental determination of the effect of mould thickness on the solidification time of aluminium alloy (Al-Mn-Ni-Si) casting in rectangular metallic moulds*.

Banchhor, R., & Ganguly, S. K. (2014a). Optimization in Green Sand Casting Process for Efficient, Economical and Quality Casting. *International Journal of Advanced Engineering Technology*, *5*(1), 25–29.

Ben David, R., Ohaion-Raz, T., Rafailov, G., Danon, A., & Finkelstein, Y. (2020). Thermal desorption kinetics of H2O and H2 from rapidly solidified Al-Zn-Mg alloy powders. *Thermochimica Acta*, *686*(February), 178554. https://doi.org/10.1016/j.tca.2020.178554

Brezina, P. (1982). Heat treatment of complex aluminium bronzes. *International Metals Reviews*, *27*(1), 77–120. https://doi.org/10.1179/imr.1982.27.1.77

Brown, J. R. (n.d.). *Foundryman ' s Handbook Edited by*.

Cahyono, A., Irawan, A. and Munir, B. (2021) "A failure analysis study on the flange of submersible vertical pump ASTM A234 operated in offshore platform," PROCEEDINGS OF THE 13TH AUN/SEED-NET REGIONAL CONFERENCE ON MATERIALS (RCM 2020) AND THE 1ST INTERNATIONAL CONFERENCE ON MATERIALS ENGINEERING AND MANUFACTURING (ICMEM 2020) [Preprint]. Available at: https://doi.org/10.1063/5.0066655.

Callcut, V. (1996). The Brasses - Properties and applications (CDA Publication No117). *The Brasses - Properties and Applications*, *117*, 35–44. http://copperalliance.org.uk/docs/librariesprovider5/resources/pub-117---the-brasses_whole_web-pdf.pdf?sfvrsn=0

Campbell, J. (2004). *Castings Practice The 10 Rules of Castings*. Elsevier/Butterworth-Heinemann, 2004.

Chakrabarti, D., Chakrabarti, A. K., & Roy, S. K. (2019). Improving the Quality of Cast Ingot for the Production of Defect-Free Rolled and Polished Blanks of Silver-Copper Coinage Alloy. *Journal of The Institution of Engineers (India): Series C*, *100*(3), 473–479.

Chen, F., Chen, S., Dong, X. H., Li, C. Y., Hong, X. T., & Zhang, X. P. (2015a). Size effects on tensile strength of aluminum-bronze alloy at room temperature. *Materials and Design*, *85*, 778–784. https://doi.org/10.1016/j.matdes.2015.06.169

Chen, F., Chen, S., Dong, X. H., Li, C. Y., Hong, X. T., & Zhang, X. P. (2015b). Size effects on tensile strength of aluminum–bronze alloy at room temperature. *Materials & Design*, *85*, 778–784.

Chen, H., Guo, N., Xu, K., Xu, C., Zhou, L., & Wang, G. (2020). In-situ observations of melt degassing and hydrogen removal enhanced by ultrasonics in underwater wet welding. *Materials and Design*, *188*, 108482. https://doi.org/10.1016/j.matdes.2020.108482

Deshmukh, V. S. (2015). The critical casting defect in cast iron: sand inclusion - A review. *International Journal of Mechanical Engineering and Technology*, *6*(9), 30–42.

Ding, Y., Lv, Y., Chen, K., Zhao, B., Han, Y., Wang, L., & Lu, W. (2018). Effects of microstructure on the stress corrosion cracking behavior of nickel-aluminum bronze alloy in 3.5% NaCl solution. *Materials Science and Engineering A*, *733*(July), 361–373. https://doi.org/10.1016/j.msea.2018.07.066

Ding, Y., Lv, Y., Zhao, B., Han, Y., Wang, L., & Lu, W. (2018). Response relationship between loading condition and corrosion fatigue behavior of nickel-aluminum bronze alloy and its crack tip damage mechanism. *Materials Characterization*, *144*(July), 356–367. https://doi.org/10.1016/j.matchar.2018.07.033

Dobrzański, L. A., Król, M., & Tański, T. (2010). Influence of cooling rate on crystallization, structure and mechanical properties of MCMgAl6Zn1 alloy.

Structure, *14*, 16.

El-Mahallawi, I. S.-E., Mahmoud, T. S., Gaafer, A. M., & Mahmoud, F. H. (2015). Effect of pouring temperature and water cooling on the thixotropic semi-solid microstructure of A319 aluminium cast alloy. *Materials Research*, *18*, 170–176.

El-Mahallawi, I. S. E. D., Mahmoud, T. S., Gaafer, A. M., & Mahmoud, F. H. (2015). Effect of pouring temperature and water cooling on the thixotropic semi-solid microstructure of A319 aluminium cast alloy. *Materials Research*, *18*(1), 170–176. https://doi.org/10.1590/1516-1439.304114

Fang, H., Tang, Q., Zhang, Q., Gu, T., & Zhu, M. (2019). Modeling of microstructure and microsegregation formation during solidification of Al-Si-Mg alloys. *International Journal of Heat and Mass Transfer*, *133*, 371–381. https://doi.org/10.1016/j.ijheatmasstransfer.2018.12.124

Fonlupt, S., Bayle, B., Heuze, J.-L., & Delafosse, D. (2003). Stress Corrosion Behaviour Of A Nickel-Aluminium Bronze In Saline Water. *Edem 2003*.

Fu, Z., Yang, W., Zeng, S., Guo, B., & Hu, S. (2016). Identification of constitutive model parameters for nickel aluminum bronze in machining. *Transactions of Nonferrous Metals Society of China*, *26*(4), 1105–1111.

Gao, F., Xu, C., Ji, G. F., Yang, M. J., & Ma, C. L. (2016). Influence of Processing Procedure on Mechanical Properties of A319 by Comparison between Casting and Powder Metallurgy. *Materials Science Forum*, *850*, 841–845.

Gede Sugita, I. K., Soekrisno, R., Made Miasa, I., & Suyitno, S. (2010). The effect of solidification rate on morphology microstructures and mechanical properties of 80%Cu-20%Sn bronze alloys. *Material Science Research India*, *7*(1), 59–66. https://doi.org/10.13005/msri/070106

Groover, M. P. (2017). Shaping Processes for Plastics: Injection Molding. *Fundamentals of Modern Manufacturing: Materials, Processes and Systems*, 287.

Guide to Nickel Aluminium Bronze for Engineers. (2016).

Hadi, N., & Al Hasan, J. (2008). *Study the effect of pH and TDS on The Corrosion Rate of Carbon Steel*. https://www.researchgate.net/publication/328466243

Hansson, C. M. (1989). Cast iron technology. In *Materials Science and Engineering: A* (Vol. 114). https://doi.org/10.1016/0921-5093(89)90868-x

Hao, Q. B., Li, C. S., Liu, G. Q., Xu, X. Y., Jiao, G. F., Zheng, H. L., Zhang, S. N., & Bai, L. F. (2018). Effect of high-temperature vacuum degassing on microstructure and current-carrying capacity of the Bi-2212 wire. *Journal of Alloys and Compounds*, *742*, 897–902.

Harry J. Meigh. (2000). Aluminium Bronzes Properties*, Processes And Structure* (Vol. 1).

Hazra, M., & Balan, K. P. (2016). Failure of a nickel aluminium bronze (NAB) canned motor pump impeller working under polluted sea water–Influence of material selection, section thickness dependent microstructure and temper annealing heat treatment. *Engineering Failure Analysis*, *70*, 141–156.

Heydarzadeh Sohi, M., Hojjatzadeh, S. M. H., Khodayar, A., & Amadeh, A. (2017). Liquid phase surface alloying of a nickel aluminum bronze alloy with titanium. *Surface and Coatings Technology*, *325*, 617–626. https://doi.org/10.1016/j.surfcoat.2017.07.019

Ignacio, M., & Perna, R. (2015). *TAILORING PROPERTIES TO REPRESENT HPDC TENSILE AND FATIGUE BEHAVIOUR IN ALUMINIUM-SILICON CAST ALLOY PROTOTYPES Martin Ignacio Riestra Perna EXAM WORK 2015*. *00*(vx).

Ishak, N. N. M., Salleh, M. S., Yahaya, S. H., Mohamad, E., & Sulaiman, M. A. (2017). The effect of equal channel angular pressing (ECAP) on the microstructure and hardness of A356 aluminium alloy. *Journal of Advanced Manufacturing Technology*, *11*(2), 47–58.

Iwamoto, K., Yamasaki, M., & Kawamura, Y. (2007). Vacuum degassing behavior of rapidly solidified Al – Mn – Zr alloy powders. 451, 1013–1017. https://doi.org/10.1016/j.msea.2006.02.252

Ivan Richardson (2016) Guide for Nickel Aluminum Bronze for Engineers. Copper Development Association

Kavinjr, Rashidi, M. M., & Ahmad, A. H. (2019). Investigation of nickel aluminium bronze castings properties by degassing agent technique. *IOP Conference Series: Materials Science and Engineering*, *469*(1). https://doi.org/10.1088/1757-899X/469/1/012037

Kim, T. S., Suryanarayana, C., & Chun, B. S. (2000). Effect of alloying elements and degassing pressure on the structure and mechanical properties of rapidly solidified Al-20Si-5Fe-2x (X = Cr, Zr, or Ni) alloys. *Materials Science and Engineering A*, *278*(1–2), 113–120. https://doi.org/10.1016/s0921-5093(99)00589-4

Kolahdooz, A., & Aminian, S. (2019). Effects of important parameters in the production of Al-A356 alloy by semi-solid forming process. *Journal of Materials Research and Technology*, *8*(1), 189–198. https://doi.org/10.1016/j.jmrt.2017.11.005

Kula, A., Blaz, L., & Sugamata, M. (2015). An analysis of the microstructure and mechanical properties of rapidly solidified Al-1Fe-1Ni-5Mg alloy. *Key Engineering Materials*, *641*, 3–9.

Kuppahalli, P., Keshavamurthy, R., Sriram, P., & Kavya, J. T. (2019). Microstructural and Mechanical behaviour of Nickel Aluminum Bronze alloys. *IOP Conference Series: Materials Science and Engineering*, *577*(1). https://doi.org/10.1088/1757-899X/577/1/012044

Level, B., & Harding, R. A. (1994). *The Freezing of Castings 3204 The Freezing of*

Castings.

Li, J. W., Ma, X., Yang, L. L., Teng, Y. L., Li, F., & Meng, L. H. (2018). Degassing of Pure Copper Melt by Ultrasonic Cavitation. *IOP Conference Series: Materials Science and Engineering*, *389*(1), 12025.

Li, H. and Chen, X. (2022) "Research progress in corrosion behavior of nickel aluminum bronze alloys in seawater," Wear, 498-499, p. 204344. Available at: https://doi.org/10.1016/j.wear.2022.204344.

Li, Y., Lian, Y. and Sun, Y. (2021) "Synergistic effect between cavitation erosion and corrosion for friction stir processed nial bronze in artificial seawater," Metals and Materials International, 27(12), pp. 5082–5094. Available at: https://doi.org/10.1007/s12540-020-00916-1.

Li, Y., Zhou, R., Li, L., Xiao, H., & Jiang, Y. (2018). Microstructure and properties of semi-solid ZCuSn10P1 alloy processed with an enclosed cooling slope channel. *Metals*, *8*(4). https://doi.org/10.3390/met8040275

Liu, X., Li, H. and Chen, X. (2022) "Corrosion Behavior of Heat-Treated Nickel-Aluminum Bronze and Manganese-Aluminum Bronze in Natural Waters," Wear, 498-499, p. 204344. Available at: https://doi.org/10.1016/j.wear.2022.204344.

Liang, G., Ali, Y., You, G., & Zhang, M. X. (2018). Effect of cooling rate on grain refinement of cast aluminium alloys. *Materialia*, *3*(August), 113–121. https://doi.org/10.1016/j.mtla.2018.08.008

Liu, X., Zhang, C., Zhang, Z., Xue, J., & Le, Q. (2017). The role of ultrasound in hydrogen removal and microstructure refinement by ultrasonic argon degassing process. *Ultrasonics Sonochemistry*, *38*(March), 455–462. https://doi.org/10.1016/j.ultsonch.2017.03.041

LIU, Y. L., & KANG, S. B. (1997). The solidification process of Al–Mg–Si alloys. *Journal of Materials Science*, *32*(6), 1443–1447. https://doi.org/10.1023/A:1018545732009

Luo, Q., Qin, Z., Wu, Z., Shen, B., Liu, L., & Hu, W. (2018). The corrosion behavior of Ni-Cu gradient layer on the nickel aluminum-bronze (NAB) alloy. *Corrosion Science*, *138*(May 2017), 8–19. https://doi.org/10.1016/j.corsci.2018.03.050

Luo, Q., Wu, Z., Qin, Z., Liu, L., & Hu, W. (2017a). Surface modification of nickel-aluminum bronze alloy with gradient Ni-Cu solid solution coating via thermal diffusion. *Surface and Coatings Technology*, *309*, 106–113.

Luo, Q., Wu, Z., Qin, Z., Liu, L., & Hu, W. (2017b). Surface modification of nickel-aluminum bronze alloy with gradient Ni-Cu solid solution coating via thermal diffusion. *Surface and Coatings Technology*, *309*, 106–113. https://doi.org/10.1016/j.surfcoat.2016.11.013

Luo, Q., Zhang, Q., Qin, Z., Wu, Z., Shen, B., Liu, L., & Hu, W. (2018). The

synergistic effect of cavitation erosion and corrosion of nickel-aluminum copper surface layer on nickel-aluminum bronze alloy. *Journal of Alloys and Compounds*, *747*, 861–868. https://doi.org/10.1016/j.jallcom.2018.03.103

Ma, S., Fu, L., Ma, X., & Shan, A. (2019). Ultra-strong nickel aluminum bronze alloys with ultrafine microstructures by continuous heavy hot rolling. *Materials Characterization*, *158*(800), 109986. https://doi.org/10.1016/j.matchar.2019.109986

Madden-Nadeau, A. L., & Genge, M. J. (2019). Fiamme degassing structures and their implications for the post-emplacement temperatures and H2O contents of high-grade ignimbrites. *Journal of Volcanology and Geothermal Research*, *384*, 251–262. https://doi.org/10.1016/j.jvolgeores.2019.08.003

Madhubala, A. and Thillairajan, K. (2022) "Al–ni duplex ion implantation of Nickel Aluminum Bronze (NAB) to improve the corrosion properties," Springer Proceedings in Materials, pp. 1–11. Available at: https://doi.org/10.1007/978-981-16-3297-6_1.

Maizza, G., Caporale, A., Polley, C., & Seitz, H. (2019). Micro-macro relationship between microstructure, porosity, mechanical properties, and build mode parameters of a selective-electron-beam-melted ti-6al-4v alloy. *Metals*, *9*(7), 786. https://doi.org/10.3390/met9070786

Malhotra, V., & Kumar, Y. (n.d.). Casting Defects: An Literature Review. In *International Journal of Design and Manufacturing Technology (IJDMT)* (Vol. 7, Issue 1). http://www.iaeme.com/IJDMT/index.asp60http://www.iaeme.com/IJDMT/issues.asp?JType=IJDMT&VType=7&IType=1JournalImpactFactor

Manikandan, R., Kumaresh Babu, S. P., Murali, M., & Vallimanalan, A. (2019). Investigation of microstructure and mechanical properties in Nickel aluminium Bronze alloy with Nb and y for aqueous applications. *Materials Today: Proceedings*, *27*(xxxx), 2591–2595. https://doi.org/10.1016/j.matpr.2019.10.173

Mian, R., ZHANG, L., WU, G., LI, W., ZHANG, X., SUN, J., & DING, W. (2019). Effect of refining processes on inclusions and mechanical properties of cast Al-2Li-2Cu-0.2 Zr alloy. *Transactions of Nonferrous Metals Society of China*, *29*(7), 1375–1382.

Ming, L., Yuan-Dong, L., Wen-Long, Y., Yu, Z., & Zong-Gang, W. (2019). Effects of Forming Processes on Microstructures and Mechanical Properties of A356 Aluminum Alloy Prepared by Self-inoculation Method. *Materials Research*, *22*(3), 1–11. https://doi.org/10.1590/1980-5373-MR-2018-0698

Mpanza, Z., Nyembwe, D., & Nel, H. (2013). Investigating the Impact of poor utilisation of quality management system in a South African foundry. *SAIIE25 Proceedings*.

Murray, T., Thomas, S., Wu, Y., Neil, W., & Hutchinson, C. (2020). Selective laser

melting of nickel aluminium bronze. *Additive Manufacturing*, *33*. https://doi.org/10.1016/j.addma.2020.101122

Nabiałek, M. G., Dośpiał, M. J., Szota, M., Pietrusiewicz, P., & Jdryka, J. (2011). Investigation of the thermal and magnetic properties of Fe 61Co10Zr2 Fe61Co10Zr 2.5Hf2.5Me2W2B20 (Me = Y, Nb, W, Ti, Mo, Ni) bulk amorphous alloys obtained by an induction suction method. *Journal of Alloys and Compounds*, *509*(7), 3382–3386. https://doi.org/10.1016/j.jallcom.2010.12.075

Nair, S., Sellamuthu, R., & Saravanan, R. (2018). Effect of Nickel content on hardness and wear rate of surface modified cast aluminum bronze alloy. *Materials Today: Proceedings*, *5*(2), 6617–6625. https://doi.org/10.1016/j.matpr.2017.11.317

Nasuha, M., Ab, B. I. N., & Mmd, H. (n.d.). *A Study of Nickel Aluminium Bronze on Microstructure & Properties Fabricated by Metal Casting Process*. *Mmd 20002*.

Nwaeju, C. C. (2019). *International Journal of Research in Engineering and Innovation Effect of nickel addition on the structure and mechanical properties of aluminium bronze (cu-10 % al) alloy*. *January*.

Obmann, R., Schörpf, S., Gorsche, C., Liska, R., Fey, T., & Konegger, T. (2019). Porous polysilazane-derived ceramic structures generated through photopolymerization-assisted solidification templating. *Journal of the European Ceramic Society*, *39*(4), 838–845. https://doi.org/10.1016/j.jeurceramsoc.2018.11.045

Ocejo, Ignacio Cobo, Moraleda, Maria Victoria Biezma, Linhardt, Paul. (2022). Corrosion behaviour of heat-treated Nickel Alluminum Bronze and Manganese Aluminum Bronze in natural waters. *Metals*. 12, 3, 380. doi 10.3390/met12030380.

Orzolek, Sean M, Semple, Jennifer K., Fisher, Charles R. (2022). Influence of processing on the microstructure of nickel aluminum bronze (NAB). *Additive Manufacturing*. 56, 102859. doi.10.1016/j.addma.2022.102859

Parameswaran, P., Rameshbabu, A. M., Navaneetha Krishnan, G., Yogeshwaran, R., & Ramkumar, R. (2018). Study of the corrosion properties in a hot forged Cu-Al-Ni alloy with added Cr. *Journal of the Mechanical Behavior of Materials*, *27*(3–4). https://doi.org/10.1515/jmbm-2018-0016

Pieprzyca, J., Kudliński, Z., & Merder, T. (2015). Effect of temperature fields heterogeneity in the tundish on primary structure of continuously cast ingots. *Archives of Metallurgy and Materials*, *60*(1), 227–233. https://doi.org/10.1515/amm-2015-0036

Pola, A., Tocci, M., & Kapranos, P. (2018). Microstructure and properties of semi-solid aluminum alloys: A literature review. *Metals*, *8*(3). https://doi.org/10.3390/met8030181

Poszytek, A., Rybak-Ostrowska, B., Łukaszewski, P., & Włodarczyk, M. (2020). Gas

trap stability in the Zechstein Limestone from the Rudna Copper Mine (SW Poland). *International Journal of Earth Sciences*, *109*(2), 439–463.

Prathvi, B., Sushma, T., & Matijević, B. (2017). Effect of heat treatment parameters on the mechanical properties and microstructure of aluminium bronze. *Tehnički Glasnik - Technical Journal*, *11*(3), 107–110.

Pub, C. D. A. (2000). Resistance to Wear of Aluminium Bronzes Resistance to Wear of Aluminium Bronzes. *Copper Development Association*.

Rajkolhe, R., Khan, J. G., & Professor, A. (2014). Defects, Causes and Their Remedies in Casting Process: A Review. *International Journal of Research in Advent Technology*, *2*(3), 2321–9637.

Raju, D., Govindan, A. R., Subramanian, J., Ramachandran, S., & Nair, S. (2019). Surface alloying of aluminium bronze with chromium: Processing, testing, and characterization. *Materials Today: Proceedings*, *27*(xxxx), 2191–2199. https://doi.org/10.1016/j.matpr.2019.09.094

Rashidi, M. M., & Idris, M. H. (2014). The effects of solidification on the microstructure and mechanical properties of modified ductile Ni-resist iron with a high manganese content. *Materials Science and Engineering: A*, *597*, 395–407.

Ren, Y., Ma, W., Wei, K., Yu, W., Dai, Y., & Morita, K. (2014). Degassing of aluminum alloys via the electromagnetic directional solidification. *Vacuum*, *109*, 82–85. https://doi.org/10.1016/j.vacuum.2014.06.026

Richardson, I. (n.d.). Guide to Nickel Aluminium Bronze for Engineers; 2016. *Copper Development Association*.

Ridhwan, J., Hamzah, E., Effendy, H., Selamat, M. Z., & Zulfattah, Z. (2013). Effect of cooling rate on the microstructures and hardness of Fe-Ni-Cr superalloy. *Journal of Mechanical Engineering and Technology*, *5*(1), 45–57.

Rundquist, V., Paci, M., & Von Gal, R. (2019). The Development of an Ultrasonic Degassing Process for Aluminium Casting. *Materials Today: Proceedings*, *10*, 288–295. https://doi.org/10.1016/j.matpr.2018.10.408

Sabbaghzadeh, B., Parvizi, R., Davoodi, A., & Moayed, M. H. (2014a). Corrosion evaluation of multi-pass welded nickel-aluminum bronze alloy in 3.5% sodium chloride solution: A restorative application of gas tungsten arc welding process. *Materials and Design*, *58*, 346–356. https://doi.org/10.1016/j.matdes.2014.02.019

Sabbaghzadeh, B., Parvizi, R., Davoodi, A., & Moayed, M. H. (2014b). Corrosion evaluation of multi-pass welded nickel–aluminum bronze alloy in 3.5% sodium chloride solution: A restorative application of gas tungsten arc welding process. *Materials & Design*, *58*, 346–356.

Safian, M. A. H., Salleh, M. S., Subramonian, S., Hussein, N. I. S., Sulaiman, M. A., & Yahaya, S. H. (2017). Production of LM4 feedstock for thixoforming using cooling

slope casting. *Journal of Advanced Manufacturing Technology*, *11*(1).

Sahoo, S., & Agrawal, A. (2020). Analysis of Crack Formation in the Casting: A Review. *International Journal of Electrical Engineering and Technology*, *11*(10), 145–151. https://doi.org/10.34218/IJEET.11.10.2020.019

Saikaew, C., & Wiengwiset, S. (2012). Optimization of molding sand composition for quality improvement of iron castings. *Applied Clay Science*, *67–68*, 26–31. https://doi.org/10.1016/j.clay.2012.07.005

Shen, C., Pan, Z., Ding, D., Yuan, L., Nie, N., Wang, Y., Luo, D., Cuiuri, D., van Duin, S., & Li, H. (2018). The influence of post-production heat treatment on the multi-directional properties of nickel-aluminum bronze alloy fabricated using wire-arc additive manufacturing process. *Additive Manufacturing*, *23*(July), 411–421. https://doi.org/10.1016/j.addma.2018.08.008

Singh, B., Korstad, J., & Sharma, Y. C. (2012). A critical review on corrosion of compression ignition (CI) engine parts by biodiesel and biodiesel blends and its inhibition. *Renewable and Sustainable Energy Reviews*, *16*(5), 3401–3408. https://doi.org/10.1016/j.rser.2012.02.042

Sithole, C., Nyembwe, K., & Olubambi, P. (2019). Process knowledge for improving quality in sand casting foundries: A literature review. *Procedia Manufacturing*, *35*, 356–360. https://doi.org/10.1016/j.promfg.2019.05.052

Tavares, S. S. M., Mota, N. M., da Igreja, H. R., Barbosa, C., & Pardal, J. M. (2021). Microstructure, mechanical properties, and brittle fracture of a cast nickel-aluminum-bronze (NAB) UNS C95800. *Engineering Failure Analysis*, *128*. https://doi.org/10.1016/j.engfailanal.2021.105606

Thapliyal, S., & Dwivedi, D. K. (2016). Microstructure evolution and tribological behavior of the solid lubricant based surface composite of cast nickel aluminum bronze developed by friction stir processing. *Journal of Materials Processing Technology*, *238*, 30–38.

Tian, Ye., Zhao, Hang., Yang, Rui., Liu, Xiaomei., Li, Hua., Chen, Xiuyong. (2022). Effect of Bacillus sp. adhesion on cavitation erosion behaviour of nickel aluminum bronze in artifical seawater. 498-499, 204344. doi 10.1016/j.wear.2022.204344

Triyono, T., Muhayat, N., Supriyanto, A., & Lutiyatmi, L. (2017). Effect of degassing treatment on the interfacial reaction of molten aluminum and solid steel. *Archives of Foundry Engineering*, *17*(2), 227–239. https://doi.org/10.1515/afe-2017-0080

Uludağ, M., Çetin, R., Dispinar, D., & Tiryakioğlu, M. (2018). The effects of degassing, grain refinement & Sr-addition on melt quality-hot tear sensitivity relationships in cast A380 aluminum alloy. *Engineering Failure Analysis*, *90*(October 2017), 90–102. https://doi.org/10.1016/j.engfailanal.2018.03.025

Vaško, A., & Vaško, M. (2016). Correlation between shape factor and mechanical properties of graphitic cast irons. *Production Engineering Archives*, *11*, 11–14.

https://doi.org/10.30657/pea.2016.11.03

Vukovic, G., & Gamweger, K. (2017). A Gas Purging System for Copper and Aluminum Furnaces. *JOM*, *69*(6), 1007–1012.

Wang, Y., Pang, X., Cao, X., Huang, J., Wanjara, P., & Gholipour, J. (n.d.). *Corrosion performance of a nickel aluminum bronze alloy refurbished using laser additive manufacturing*.

Wauthier, C., Smets, B., Hooper, A., Kervyn, F., & d'Oreye, N. (2018). Identification of subsiding areas undergoing significant magmatic carbon dioxide degassing, along the northern shore of Lake Kivu, East African Rift. *Journal of Volcanology and Geothermal Research*, *363*, 40–49. https://doi.org/10.1016/j.jvolgeores.2018.08.018

Wharton, J. A., Barik, R. C., Kear, G., Wood, R. J. K., Stokes, K. R., & Walsh, F. C. (2005). The corrosion of nickel-aluminium bronze in seawater. *Corrosion Science*, *47*(12), 3336–3367. https://doi.org/10.1016/j.corsci.2005.05.053

Wu, X., Wang, R., Peng, C., & Wang, X. (2020). Low-temperature annealing behavior and tensile properties of the rapidly solidified Cu3Ag0.5Zr0.4Cr0.35Nb alloy reinforced by cold rolling. *Journal of Alloys and Compounds*, *828*, 154371. https://doi.org/10.1016/j.jallcom.2020.154371

Wu, X., Wang, R., Peng, C., & Zeng, J. (2020). Ultrafine grained Cu–3Ag-xZr (x = 0.5, 1.0 wt%) alloys with high strength and good ductility fabricated through rapid solidification and cryorolling. *Materials Science and Engineering A*, *778*(December 2019), 139095. https://doi.org/10.1016/j.msea.2020.139095

Wu, Z., Cheng, Y. F., Liu, L., Lv, W., & Hu, W. (2015a). Effect of heat treatment on microstructure evolution and erosion-corrosion behavior of a nickel-aluminum bronze alloy in chloride solution. *Corrosion Science*, *98*, 260–270. https://doi.org/10.1016/j.corsci.2015.05.037

Wu, Z., Cheng, Y. F., Liu, L., Lv, W., & Hu, W. (2015b). Effect of heat treatment on microstructure evolution and erosion–corrosion behavior of a nickel–aluminum bronze alloy in chloride solution. *Corrosion Science*, *98*, 260–270.

wwwantimicrobialcoppercom. (n.d.). *A Guide to Working With Copper and Copper Alloys*. www.antimicrobialcopper.com

Wu, Z. et al. (2021) "Effect of plastic deformation on mechanical properties and corrosion resistance of nickel-aluminum bronze," Anti-Corrosion Methods and Materials, 68(6), pp. 473–480. Available at: https://doi.org/10.1108/acmm-12-2020-2411.

Xu, X., Lv, Y., Hu, M., Xiong, D., Zhang, L., Wang, L., & Lu, W. (2016). Influence of second phases on fatigue crack growth behavior of nickel aluminum bronze. *International Journal of Fatigue*, *82*, 579–587.

Yang, R. et al. (2022) “Corrosive properties of CuNi2SiCr fabricated through directed energy deposition on a nickel-aluminum bronze substrate,” Wear, 498-499, p. 204344. Available at: https://doi.org/10.1016/j.wear.2022.204344.

Yao, Chang-Liang, Shim, Do-Sik (2022). Corrosive properties of $CuNi_2SiCr$ fabricated through directed energy deposition on a nickel-aluminum bronze suvstrate. *Journal of Alloys and Compounds*. 91, 8-15. doi 10.1016/j.jallcom.2022.165776

Young, K. P., & Kerkwood, D. H. (1975). The dendrite arm spacings of aluminum-copper alloys solidified under steady-state conditions. *Metallurgical Transactions A*, *6*(1), 197–205. https://doi.org/10.1007/BF02673688

Zhai, W., Lu, W., Zhang, P., Zhou, M., Liu, X., & Zhou, L. (2017). Microstructure, mechanical and tribological properties of nickel-aluminium bronze alloys developed via gas-atomization and spark plasma sintering. *Materials Science and Engineering A*, *707*(September), 325–336. https://doi.org/10.1016/j.msea.2017.09.047

Zhang Chengdong, Liu Bin, Shi Zeyao, Liu Yan, Cao Qingmin, Jian Donghui (2022). Research progress in corrosion behaviour of nickel aluminum bronze alloys in seawater. *Journal of the Chinese Society of Corrosion and Protection.* 42, 1, 25-33. doi 10.11902/1005.4537.2020.221

Zhang, X., Huang, L. K., Zhang, B., Chen, Y. Z., Duan, S. Y., Liu, G., Yang, C. L., & Liu, F. (2019). Enhanced strength and ductility of A356 alloy due to composite effect of near-rapid solidification and thermo-mechanical treatment. *Materials Science and Engineering A*, *753*(January), 168–178. https://doi.org/10.1016/j.msea.2019.03.039

Zhao, B., Lv, Y., Ding, Y., Wang, L., & Lu, W. (2018). The grain refinement mechanisms of various phases in shot-peened Nickel-Aluminum bronze (NAB) alloy. *Materials Characterization*, *144*(800), 77–85. https://doi.org/10.1016/j.matchar.2018.07.002

Zhao, H. et al. (2022) “Influence of processing on the microstructure of nickel aluminum bronze (NAB),” Wear, 498-499, p. 204344. Available at: https://doi.org/10.1016/j.wear.2022.204344.

Zhao, L. et al. (2022) “The laser deposited nickel-aluminum bronze coatings on SUS630 stainless steel and its corrosion resistance in 3.5 wt.% NaCl solution,” Metals, 12(5), p. 781. Available at: https://doi.org/10.3390/met12050781.

Zheng, Y., Li, N., Yan, J., & Cao, Y. (2016). The microstructure and mechanical properties of 1Cr17Ni2/QAl7 brazed joints using Cu-Mn-Ni-Ag brazing alloy. *Materials Science and Engineering: A*, *661*, 25–31.