The Effect of Gas Venting on the Mechanical Properties of C95800 Aluminum Bronze Castings

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ABSTRACT

C95800 aluminum bronze alloy is a high-strength, corrosion-resistant, and long-lasting material, widely used in engineering applications requiring high durability. Components made from this alloy are often produced by casting, due to the ease of forming complex shapes and their cost-effectiveness. However, a major challenge in casting is that of porosity, which directly affects the mechanical properties of the finished product. Porosity, caused by gas entrapment or shrinkage during cooling, leads to structural discontinuities, ultimately reducing strength. Therefore, efforts have been made to minimize gas-related defects in C95800 aluminum bronze castings for higher quality. In this study, patterns and molds were prepared according to JIS-H 5120. Six CO_2 sand molds were used to support the molten metal during casting. A gas venting technique was applied to these molds, and a degassing agent was subsequently introduced to the molten metal, which was melted in an induction furnace with a silicon carbide crucible at approximately 1,200-1,250°C under an oxidizing atmosphere. The degassed molten metal was then rapidly poured into the sand molds and cooled during solidification. This research aims to investigate the effect of the degassing technique, in conjunction with gas venting, on the mechanical properties of C95800 aluminum bronze castings. The tensile strength, impact strength, and hardness were compared between castings produced with and without degassing to evaluate the effectiveness of these techniques in improving the casting quality. The results indicate that the combined application of gas venting and degassing significantly enhances the quality and mechanical performance of the castings.

Keywords-C95800 aluminum-bronze alloy castings; porosity; gas venting; degassing

I. INTRODUCTION

C95800 aluminum bronze is a high-performance alloy known for its excellent strength, corrosion resistance, and long service life. It is widely used in demanding engineering applications, such as marine components, seawater systems, and petrochemical industries. Due to its superior properties, casting is a common manufacturing method for producing C95800 parts, especially when complex shapes are required and economic efficiency is a priority. The chemical composition of C95800 is shown in Table I [1-3, 5-7]. However, the melting of copper and copper alloys presents a major challenge—porosity—which directly affects the mechanical properties of the final workpiece. This porosity typically occurs due to the ability of molten copper to dissolve both oxygen and hydrogen gases. During solidification, these gases react to form steam, resulting in pore formation within the casting [2-6,10].

TABLE I. CHEMICAL COMPOSITION OF ALUMINUM BRONZE ALLOYS (ASTM B148-97 [8]) AND CASTING EXAMPLES

Copper alloy UNS No.	Nominal compositions (wt. %)					
	Cu	Ni	Fe	Al	Si	Mn
C95800	79.0 (min)	4.0-5.0	3.5-4.5	8.5-9.5	0.1 (max)	0.8-1.5
Specimen	76.57	4.16	3.81	8.85	0.09	0.52

If the vapor pressure exceeds the combined pressure of the metal head height and atmospheric pressure, steam escapes through the sprue or riser in a process known as purging, mushrooming, or blowing. This phenomenon causes the top surface of the casting to bulge, as the gas separates from the melt and pushes semi-solid metal outward through overflow holes, which then solidifies in a visible form [4, 10, 15-19], , as illustrated in Figure 1. When machining such castings, defects caused by porosity become evident, as shown in Figure 2. During melting under an oxidizing atmosphere, a certain amount of oxide forms within the melt. It is, therefore, necessary to remove oxygen before pouring the metal. It is generally easier to prevent gas from dissolving into the metal during melting than to remove it afterward. Thus, an effective gas control during the melting process is critical for ensuring the desired mechanical properties of the solidified metal ingot [3, 13-17, 20].

Fig. 1. Inflated upper surface due to gas.

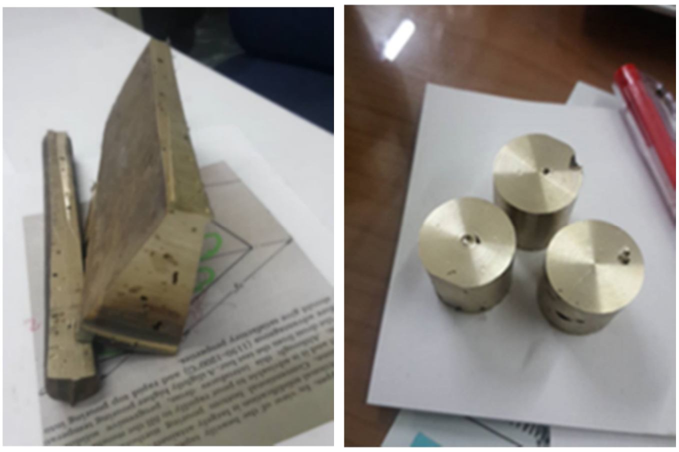


Fig. 2. Damage of the workpiece due to porosity.

To control the quality of the melt by limiting the amount of dissolved gas, various types of test rods must be produced to evaluate the material properties and confirm that the melting process meets the required standards. Typically, rods for mechanical testing are poured into cylindrical molds with diameters ranging from 25 mm to 50 mm, as displayed in Figure 3. These test rods can be cast prior to the actual workpiece to assess the shrinkage tendencies, which helps predict the shrinkage behavior of the final casting. If the top surface of the rod appears bulging, as depicted in Figure 3, it indicates a high concentration of dissolved gases.

Conversely, if shrinkage cavities appear in the form of piping, this indicates very low gas content. Proper melting should yield metal with high tensile strength, good ductility, and minimal porosity [2, 4, 10].

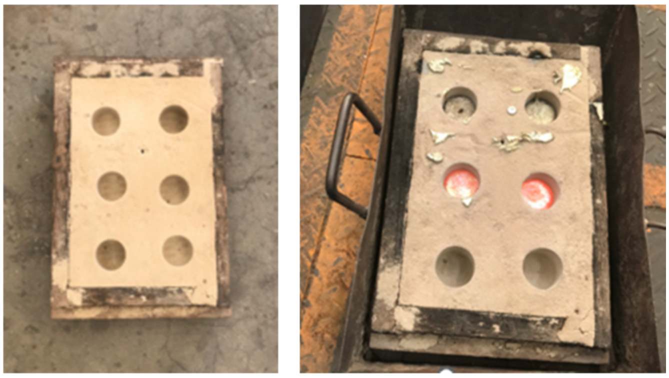


Fig. 3. Pouring of the test rods before the actual pouring.

A degassing approach was studied by adding degassing agents to the C95800 aluminum bronze alloy casting melt prior to the pouring process to reduce the amount of dissolved gases [2-3, 10, 13-14, 30-31]. Several parameters were evaluated to investigate the effects of the degassing agents. It was found that a higher cooling rate suppressed the dendrite growth and improved the mechanical properties. Furthermore, increasing the amount of degassing agent resulted in finer dendritic structures, which enhanced the mechanical strength, as confirmed by tensile and hardness tests [15]. Gas venting is, thus, considered an effective method for reducing porosity in castings, as it allows trapped gases within the mold to escape before the metal solidifies. This technique is expected to improve the casting quality and enhance the mechanical performance [15-18]. The objective of the current research is to examine the effect of gas venting on the mechanical properties of C95800 aluminum bronze castings by comparing the tensile strength, compressive strength, and hardness of vented and unvented samples, thereby evaluating the effectiveness of this approach in enhancing the overall casting quality [20-22].

II. EXPERIMENTAL PROCEDURE

In this research, an experiment was conducted by modifying the shape and size of the workpiece according to the JIS-H 5102 standard [5-6, 9], as illustrated in Figure 4. The workpiece was produced using the CO_2 sand casting process. In this process, a gas venting technique was applied by incorporating four horizontal vent holes, each with a diameter of 2 mm and a depth of approximately 3-5 mm, depending on the shape of the workpiece [20-24]. The materials used for testing included C95800 aluminum bronze casting scrap, along with degassing agents, such as Flux, Logas 50, and a deoxidizing tube E, as shown in Figure 5. The metal to be melted was required to be clean and free from oil and moisture.

A. Melting Process

The ingredients were weighed according to the calculated amount for each charge, with a melting rate of 30 kg per charge. An induction type furnace was used for melting, and the container was a silicon carbide crucible. The casting mold was made from CO_2 sand casting, as mentioned in [13-14]. The steps involved in the melting process followed the standard procedures, as outlined in [15-16, 19, 23-37, 44].

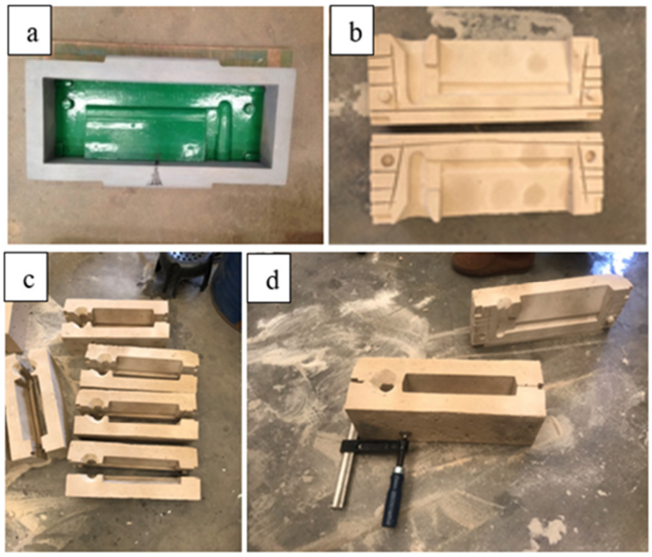


Fig. 4. Experimental assembly: (a) pattern, (b) CO_2 sand casting, (c) vent holes, (d) assembled CO_2 sand casting.

Fig. 5. Materials used for testing: (a) nickel aluminum bronze (AlBC3) scraps, (b) flux compound fluorides, (c) Logas 50 (degassing agent), (d) deoxidizing tube E.

1. The furnace was preheated to a temperature of 600 -700°C until it reached a red-hot state. Simultaneously, the nickel-aluminum bronze materials, including metal scraps, were placed on the furnace to undergo a preheating process. This step was crucial to remove any residual moisture, preventing unwanted reactions, such as hydrogen absorption, which could lead to gas-related defects in the final casting.
2. Once preheating was completed, nickel-aluminum bronze scraps were carefully loaded into silicon carbide crucibles to ensure efficient melting. The choice of silicon carbide crucibles was based on their high thermal conductivity and resistance to chemical reactions, which helped maintain the purity of the molten metal throughout the process.
3. When the nickel-aluminum bronze reached a melting temperature of 1,200°C, Logas 50 Press Submersible, a degassing agent, was introduced into the molten metal to reduce the presence of dissolved gases, particularly hydrogen and oxygen, which are known to cause porosity. After an interval of 5–10 min, Deoxidizing Tube E was added to further refine the molten metal by minimizing oxidation and ensuring an improved metal quality.
4. The temperature must be measured before pouring the melt, which should be about 1,250 ± 10°C. Regarding the flux material, 0.25-0.5% the total metal weight was applied evenly over the surface, and subsequently, the test samples were poured to assess the surface of the test specimens.
5. The chemical composition of the sample was analyzed using an Optical Emission Spectrometer. The results confirmed that the sample was a commercial aluminum-bronze alloy, grade AlBC3. The specified composition included 3.5-4.5% iron, 8.5-9.5% alumina, 4.0-5.0% nickel, 0.8-1.5% manganese, and 0.1% silica, with copper being the primary constituent.

Fig. 6. Casting process of nickel-aluminum bronze.

6. Once the specified temperature was achieved, a flux material amounting to 0.25-0.5% of the total metal weight was carefully added to the surface of the molten metal.

This flux helped to purify the melt by promoting the separation of impurities and reducing oxidation. After allowing sufficient time for the flux to react, the slag formed on the surface was thoroughly removed to ensure a clean pour. The purified molten metal was then poured rapidly and continuously into the CO_2 sand mold to prevent premature solidification and minimize the risk of defects, such as porosity or incomplete filling.

7. When the molten metal had been poured into the casting mold, the workpiece was left to cool inside the mold. Afterwards, the CO_2 sand casting mold was dismantled, and the testing specimens were removed. A visual inspection was performed, and the casting was cleaned by sandblasting, as shown in Figure 6.

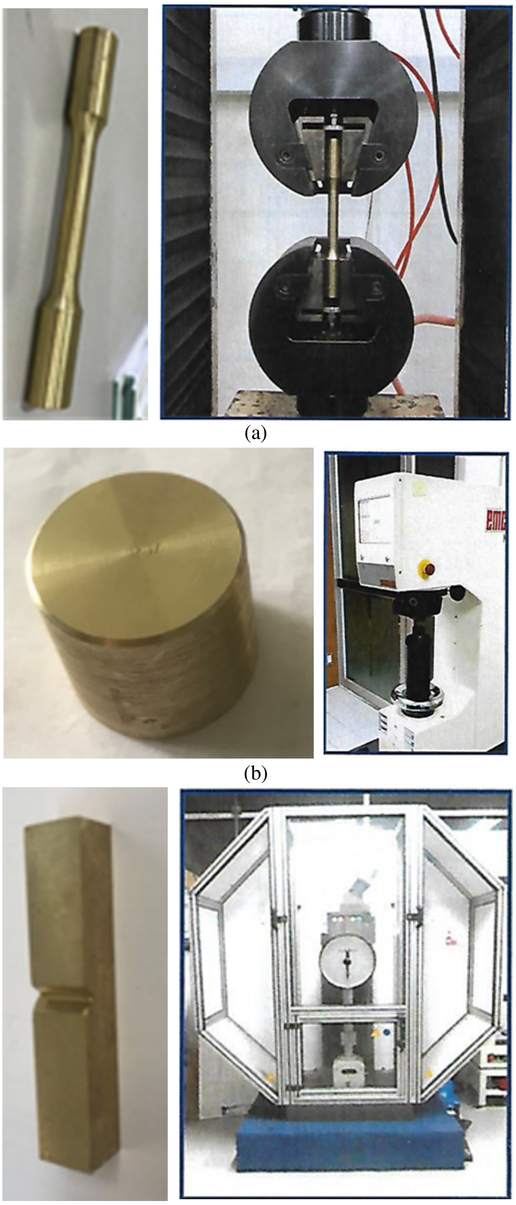
The workpiece was subsequently cut and machined to the specified dimensions, as illustrated in Figure 7. This preparation was carried out to facilitate the evaluation and analysis of its mechanical properties through standardized testing methods [11-12].

Fig. 7. Casting and machining of pieces.

III. RESULTS

The tensile strength test (ASTM E8) was performed to determine the Ultimate Tensile Strength (UTS), yield strength, and elongation of the material. The specimens were subjected to uniaxial tensile loading until fracture to assess their mechanical integrity and ductility.

The Rockwell Hardness Test (HRB) was conducted using the Rockwell Hardness Scale B (HRB) to evaluate the material's resistance to deformation. This test provides insights into the alloy's strength and wear resistance, which are critical for industrial applications. The Charpy Impact Test (ASTM E23) was conducted to measure the impact toughness of the material using a notched specimen. This test measures the energy absorbed by the sample when subjected to a sudden impact load, providing valuable information on its fracture resistance and brittleness. As displayed in Figure 8, each test was conducted using three specimens to ensure the repeatability and reliability of the results. The obtained data were analyzed to compare the mechanical performance of the nickel-aluminum bronze cast samples with standard industrial benchmarks [29, 33-36, 43].



(a)

(b)

(c)

Fig. 8. Testing setup: (a) tensile strength test, (b) HRB, (c) Charpy Impact Test.

TABLE II. MECHANICAL PROPERTY COMPARISON OF VENTED VERSUS NON-VENTED C95800 ALUMINUM BRONZE CASTINGS

Materials	Tensile strength (N/mm^2)	Impact testing (J)	Hardness testing (HRB)	Elongation (%)
Without gas venting.	588	10	71	15
Gas venting Specimen1	589	12	77	18
Gas venting Specimen 2	582	12	72	15
Gas venting Specimen 3	599	15	75	13
Average Specimens 1-3	590	13	74	15.3

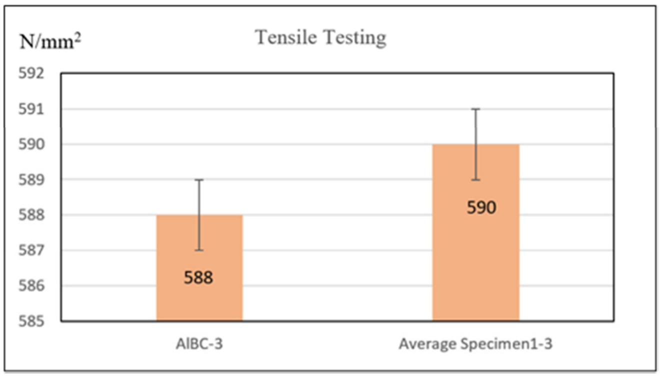


Fig. 9. Results of tensile strength testing.

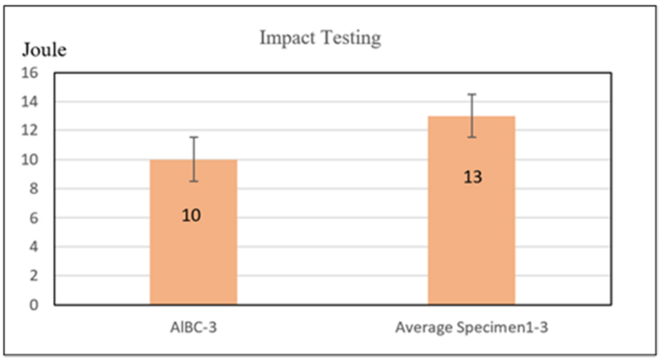


Fig. 10. Results of impact testing.

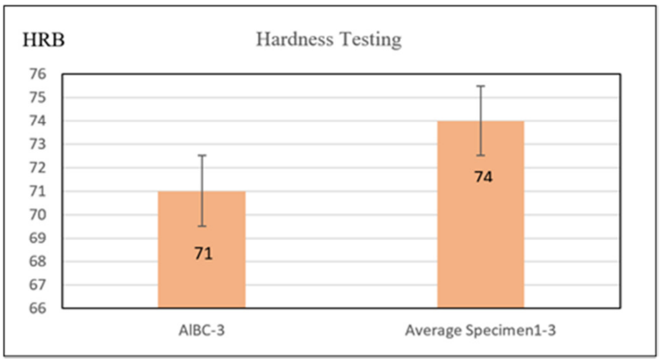


Fig. 11. Results of hardness testing.

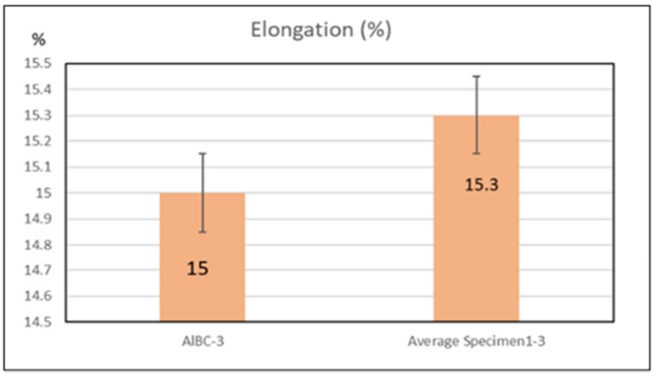


Fig. 12. Results of elongation test.

Table II and Figures 9-12 show the results from the mechanical property tests, including the tensile, hardness, and impact tests. The results showed that the average values obtained were higher than those of C95800 aluminum bronze castings without gas venting.

TABLE III. DESCRIPTIVE ANALYSIS OF MECHANICAL PROPERTIES WITH AND WITHOUT GAS VENTING

Mechanical properties	**Min**	**Max**	**Mean**	**Std. dev.**
Tensile strength (MPa)	582	599	589.5	7.05
Impact testing (J)	10	15	12.25	2.06
Hardness (HRB)	71	77	73.75	2.75
Elongation (%)	13	18	15.25	2.06

Table III presents the mechanical properties of four material groups, one without gas venting and three specimens with gas venting. The summary of these tests is as follows:

- Tensile strength test: The average tensile strength was 589.5 MPa, with the highest value of 599 MPa observed in gas venting Specimen 3 and the lowest at 582 MPa in Specimen 2.
- Impact test: The mean impact energy was 12.25 J, with the highest value of 15 J also recorded in Specimen 3, while the non-vented sample exhibited the lowest impact strength at 10 J.
- Hardness test: The mean hardness was 73.75 HRB, with the highest (77 HRB) found in Specimen 1 and the lowest (71 HRB) in the non-vented sample.
- Elongation: The average elongation was 15.25%, ranging from a minimum of 13% in Specimen 3 to a maximum of 18% in Specimen 1.

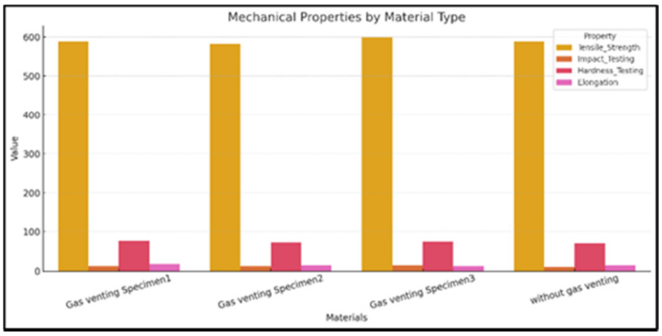


Fig. 13. Mechanical properties of material by type.

Figure 13 illustrates a comparative bar chart representing four mechanical properties, tensile strength, impact test, hardness, and elongation measured across four different material conditions: one specimen without gas venting, and three specimens with gas venting (Specimens 1-3). Each colored bar corresponds to a specific mechanical property, allowing for a direct visual comparison among the material groups. The following trends were observed:

- The gas venting specimens consistently exhibited superior mechanical performance compared to the non-vented sample.

- Specimen 3 recorded the highest tensile strength (599 MPa) and impact energy (15J).
- Specimen 1 demonstrated the highest values in hardness (77 HRB) and elongation (18%).
- The non-vented specimen exhibited the lowest values in most categories, particularly in impact energy (10 J) and hardness (71 HRB).

A. Fracture Surface Characteristics

The fracture characteristics of the specimens following the tensile test are presented in Figure 14.

(a) (b) (c)

Fig. 14. Mechanical test results: (a) tensile test, (b) hardness test, (c) impact test.

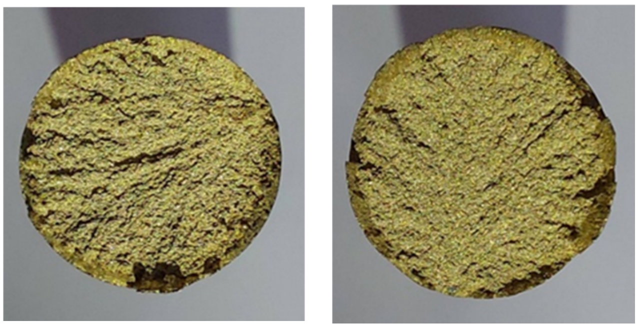


Fig. 15. Fracture characteristics visible to the naked eye.

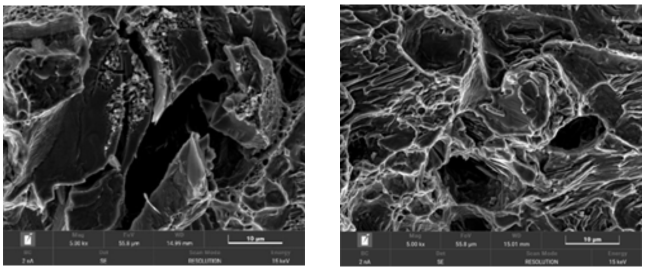


Fig. 16. Fracture morphologies of samples under SME.

The fracture surface appears linear, opaque, and dull, with visible cleavage steps and river marking-features indicative of brittle fracture. [38-42]. Surface cracking is clearly visible to the naked eye, as portrayed in Figure 15. However, the Scanning Electron Microscope (SEM) examination, as shown in Figure 16, reveals a smooth fracture surface with distinct facets. [44, 45]. Although these features confirm fracture on a macroscopic scale, the presence of localized plastic deformation is suggested, consistent with the observed percentage elongation of the specimen after the tensile test.

IV. CONCLUSIONS

The casting results indicate a minimal porosity in machined C95800 aluminum bronze alloy parts, significantly reducing gas retention issues. Gas porosity is a significant defect negatively impacting mechanical properties, such as tensile strength, ductility, and impact toughness. Eliminating porosity through optimized melting and casting yields superior mechanical performance in this specific alloy.

The study results show that proper gas venting and degassing significantly improve the tensile strength, impact toughness, and hardness of C95800 aluminum bronze castings. Gas venting yields higher tensile strength and increased toughness, indicating resistance to brittle fracture. The reduced porosity also improves hardness, indicating resistance to deformation. The optimized treatments result in harder, more durable castings due to the elimination of gas-related defects, thus optimizing casting for high-quality products with superior mechanical properties. Reduced porosity and improved mechanical properties make these castings more suitable for high-performance applications where durability and reliability are paramount.

The descriptive analysis reveals a consistent improvement in the mechanical properties for specimens produced using gas venting techniques. Gas venting significantly enhanced impact resistance, which is likely attributable to the reduction of internal porosity and the improvement in structural integrity during the solidification process. Additionally, the tensile strength and hardness exhibited noticeable increases in the vented specimens, suggesting that more uniform metallurgical bonding and fewer casting defects occurred as a result of the venting mechanism. Although elongation improved in certain cases, most notably in Specimen 1, it showed a slight decline in others, implying that ductility may also be influenced by additional factors, such as the cooling rate, alloy composition, or localized microstructural variations. These observed trends collectively underscore the importance of minimizing gas entrapment during casting in order to optimize the overall mechanical integrity and reliability of the final product.

This research provides valuable insights into the relationship between casting optimization and the mechanical properties of C95800 aluminum bronze casting. Controlling the gas content through degassing agents, the flux, and mold design can significantly improve the casting mechanical performance, with practical applications in the C95800 aluminum bronze casting industry, where high-strength, durable materials are essential.

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REFERENCES

[1] E. G. West, *Copper and its alloys*. Chichester, United Kingdom: Halsted Press, 1982.

[2] Rowley, *Casting Copper-Base Alloys*, 1st ed. Schaumburg, Illinois: American Foundrymen's Society, 1984.

[3] I. Richardson and O. Gouriou, "Nickel- bronze: A reconsideration for valve manufacture," *Valve World*, pp. 1–4, Oct. 2017.

[4] J. Callister and D. William, *Fundamentals of materials science and engineering: an integrated approach*, 2nd ed. Hoboken, New Jersey: John Wiley & Sons, 2005.

[5] H. J. Meigh, *Cast and Wrought Aluminium Bronzes: Properties, Processes and Structure*, 2nd ed. London, United Kingdom: IOM Communications, 2008.

[6] J. R. Davis, *ASM handbook 2: Properties and selection: Nonferrous Alloys and Special-Purpose Materials*, 10th ed. Materials Park, Ohio: ASM International, 1991.

[7] *Standard Specification for Aluminum-Bronze Sand Castings*, ASTM B148-97, ASTM International, West Conshohocken, Pennsylvania, Apr. 2003.

[8] *Standard Specification for Aluminum Bronze Sand Casting*, ASTM B148-18, ASTM International, West Conshohocken, Pennsylvania, 2018.

[9] J. R. Brown, *Foseco Non-Ferrous Foundryman's Handbook*, 11th ed. Oxford, United Kingdom: Butterworth-Heinemann, 1999.

[10] *JIS Handbook: Non-Ferrous Metals & Metallurgy*. Tokyo, Japan: Japanese Standards Association, 2011

[11] *Copper and Copper Alloy Casting*, Tokyo, Japan: Japanese Standards Association, 2009.

[12] *ASM handbook. 15: Casting*, 9th ed., vol. 15. Materials Park, Ohio: ASM International, 1988.

[13] D. E. Tyler, D. W. Dickinson, and E. J. Dore, "Method of Melting Copper Alloys with a Flux," U.S. Patent 4,038,068, Jul. 1977.

[14] Kavinjr, M. M. Rashidi, and A. H. Ahmad, "Investigation of nickel aluminium bronze castings properties by degassing agent technique," *IOP Conference Series: Materials Science and Engineering*, vol. 469, Jan. 2019, Art. no. 012037, https://doi.org/10.1088/1757-899X/469/1/012037.

[15] P. Wenschot, "Defects caused by precipitation of in liquid copper–nickel–aluminium–bronze alloys dissolved carbon and removal by treatment of melt," *International Journal of Cast Metals Research*, vol. 27, no. 2, pp. 65–72, Jan. 2014, https://doi.org/10.1179/1743133613Y.0000000080.

[16] P. Idodo, "Reducing Casting Defects in Pure Copper Castings," B.S. thesis, Jönköping School of Engineering, Jönköping, Sweden, 2022.

[17] W. Walkington, *Gas Porosity – A Guide to Correcting the Problems*, Rosemont, Illinois: North American Die Casting Association, 2018.

[18] M. Lagiewka and C. Kolmasiak, "The porosity of Tin bronze castings," *Metalurgija*, vol. 62, no. 1, pp. 155–157, 2023.

[19] L. Ezra, *Kolzin venting: A lost art*. Schaumburg, Illinois: Modern Casting, 1998.

[20] P. Berner, G. Metevelis, and S. Scheil, *Mold Venting: A Return to the Basics*. Schaumburg, Illinois: Modern Casting, 1997.

[21] P. King, D. Martinez, and G. P. Manogharan, "Novel Sprue Designs to Reduce Casting Defects in Nickel-Aluminum Bronze: A Computational Study," in *Additive Manufacturing; Advanced Materials Manufacturing; Biomanufacturing; Life Cycle Engineering; Manufacturing Equipment and Automation*, Sep. 2020, Art. no. V001T01A054, https://doi.org/10.1115/MSEC2020-8486.

[22] J. F. Meredith, "Solidification and feeding of copper-base castings," *Metal Casting Technologies*, vol. 52, no. 4, pp. 44–46, 2006.

[23] J. Campbell, *Complete casting handbook: metal casting processes, techniques and design*, 2nd ed. Amsterdam, Netherlands: Elsevier, 2015.

[24] J. F. Meredith, "Casting of copper-base casting," *Metal Casting Technologies*, vol. 53, no. 4, pp. 58–60, 2007.

[25] B. Friedrich, C. Kräutlein, and K. Krone, "Melt Treatment of Copper and Aluminium – The Complex Step Before Casting," in *Continuous Casting*, H. R. Müller, Ed., 1st ed., Hoboken, New Jersey: John Wiley & Sons, 2005, pp. 1–22.

[26] A. Sami and N. Ahmed, "Study on Improvement of Casting Conditions for Some Aluminum Bronze Alloys," *Engineering and Technology Journal*, vol. 25, no. 6, pp. 711–727, Jun. 2007, https://doi.org/10.30684/etj.25.6.3.

[27] S. Alam, R. I. Marshall, and S. Sasaki, "Metallurgical and tribological investigations of aluminium bronze bushes made by a novel centrifugal casting technique," *Tribology International*, vol. 29, no. 6, pp. 487–492, Sep. 1996, https://doi.org/10.1016/0301-679X(95)00108-G.

[28] F. Hasan, J. Iqbal, and N. Ridley, "Microstructure of as-cast aluminium bronze containing iron," *Materials Science and Technology*, vol. 1, no. 4, pp. 312–315, Apr. 1985, https://doi.org/10.1179/mst.1985.1.4.312.

[29] K. S. Abdei-Wahab, E. M. E. Banna, A. A. Hussein, and M. Waly, "Effect of chromium and silicon additions on the microstructure and mechanical properties of complex aluminum bronze," *International Journal of Metallurgical & Materials Science and Engineering*, pp. 18–27, 2015.

[30] E. C. Chia, "Investigation of Gas Equilibria in Copper," M.S. thesis, Georgia Institute of Technology, Atlanta, Georgia, United States, 1967.

[31] E. F. Brush, S. P. Midson, W. G. Walkington, D. T. Peters, and J. G. Cowie, *Porosity Control in Copper Rotor Die Castings*. Geumcheon-gu, Seoul, Korea: Castman, 2010.

[32] M. Sahoo and S. Sahu, *Principles of Metal Casting, Third Edition*, 3rd edition. New York, New York State: McGraw-Hill Education, 2014.

[33] G. Adeyemi, B. S. Oluwadare, and K. O. Olanipekun, "Investigation on the effect of addition of magnesium on the microstructure and mechanical properties of aluminum bronze," *International Journal of Engineering Science Invention*, vol. 2, no. 11, pp. 1–13, Nov. 2013.

[34] A. A. Imah, S. C. Ekenyem, C. C. Ogbu, G. O. Ewa, and E. E. Nnuka, "Effects of Nickel on the Structure and Mechanical Properties of Aluminum Bronze (Cu-10wt%Al)," *International Journal of Engineering Inventions*, vol. 9, no. 1, pp. 41–51.

[35] C.N. Nwambu, I.M. Anyaeche, G.C. Onwubiko, and E.E. Nnuka, "Modification of the structure and mechanical properties of aluminum bronze (Cu-10%Al) alloy with zirconium and titanium," *International Journal of Scientific Engineering and Research*, vol. 8, no. 1, pp. 1048–1057, 2017.

[36] M. Moradlon, N. Arab, R. Emadi, and M.M. Meratian, "Effect of magnesium and nickel on the wear and mechanical properties of casting bronzes," *Journal of American Science*, vol. 7, no. 7, pp. 717–722, 2011.

[37] S. M. Orzolek, J. K. Semple, and C. R. Fisher, "Influence of processing on the microstructure of nickel aluminum bronze (NAB)," *Additive Manufacturing*, vol. 56, Aug. 2022, Art. no. 102859, https://doi.org/10.1016/j.addma.2022.102859.

[38] D. R. Askeland, P. P. Fulay, and P. P. Fulay, *The science and engineering of materials*, 4th ed. Pacific Grove, California.: Brooks/Cole-Thomson Learning, 2003.

[39] A. Pineau and T. Pardoen, "Failure of Metals," in *Comprehensive Structural Integrity*, Amsterdam, Netherlands: Elsevier, 2007, pp. 684–797.

[40] A. Pineau, A. A. Benzerga, and T. Pardoen, "Failure of metals I: Brittle and ductile fracture," *Acta Materialia*, vol. 107, pp. 424–483, Apr. 2016, https://doi.org/10.1016/j.actamat.2015.12.034.

[41] A. K. Zurek, "Brittle cracks in intrinsically ductile copper," *Scripta Metallurgica*, vol. 21, no. 12, pp. 1619–1622, Dec. 1987, https://doi.org/10.1016/0036-9748(87)90145-1.

[42] D. François, A. Pineau, and A. Zaoui, *Mechanical Behaviour of Materials: Volume II: Fracture Mechanics and Damage*, 2nd ed. Dordrecht, Netherlands: Springer, 2013.

[43] C. Thongyothee and S. Chareonvilisiri, "A Study on the Influence of Silicon Content on Wear and Mechanical Properties of Cast Nickel-Aluminum Bronze," *Engineering, Technology & Applied Science Research*, vol. 14, no. 6, pp. 18316–18323, Dec. 2024, https://doi.org/10.48084/etasr.8817.

[44] O. Bildik and M. Yaşar, "Manufacturing of Wear Resistant Iron-Steel: A Theoretical and Experimental Research on Wear Behavior," *Engineering, Technology & Applied Science Research*, vol. 11, no. 3, pp. 7251–7256, Jun. 2021, https://doi.org/10.48084/etasr.4092.