Investigations on the Mechanical and Tribological Performance of Nickel Aluminum Bronze- CaCO₃ Composite

Vijay Bhardwaj, R Saravanan, M Govindaraju, R Vaira Vignesh

Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India

r_saravanan@cb.amrita.edu

Abstract. In the present work, commercially available Nickel Aluminum Bronze (NAB) alloy was composited with CaCO₃ through casting route. The developed composite was characterized for microstructure, micro hardness, tensile strength (room temperature and high temperature), and wear rate. The results indicate an improvement in tensile strength by 10%, micro hardness by 2.5 times, and wear resistance by 29% than that of the as-received specimen. This is attributed to the reinforcement of CaCO₃ in NAB, which in turn resulted in refinement of the grains, reduction of the β’-phase and preferential formation of intermetallic precipitates of κ-phases (κII, κIII, and κIV).

1. Introduction
Nickel Aluminum Bronze (NAB) is a copper-based alloy with the composition containing 4% to 5% of nickel, 8% to 10% of aluminum, with like iron, silicon, or manganese as a minor element. Conventionally, NAB alloys offer good mechanical strength, wear resistance, and corrosion resistance [1-4]. Hence, NAB alloys are cast to fabricate engineering components such as valves, parts of pumps, ship propellers, bearings, and gears [5-8]. However, bulk or surface modification of NAB alloys would augment their properties and hence improve the effective service life of engineering components. The as-cast NAB alloy consists of the coarse copper-rich α phase, the β’ phase (martensitic β), and various intermetallic precipitates (κII, κIII and κIV), based on Fe₃Al or NiAl [9-14]. The coarse α phase weakens the tensile strength whereas the β’ phase accelerates the fatigue crack growth rate. Besides, the β’ phase and α phase undergo preferential corrosion attacks because of galvanic couple effects in the marine environment [10-12, 14]. Furthermore, the lamellar κIII phase could make NAB alloy susceptible to crevice corrosion. Recently, introducing the uniform and refined microstructures into as-cast NAB alloy via different techniques has attracted considerable attention [6, 14-21]. In this study, the influence of CaO on the microstructural evolution, micro hardness, and Tribological performance of the NAB alloy was investigated. The major application of the composite is in the area where base metal wear out faster such as bearings, valve and also in the area where NAB used in high temperature application.

2. Materials and Methodology
In this study, commercially available NAB was used as the base material. The composition of the NAB alloy, which was determined using arc spectroscopy, is given in table 1.

| Element | Cu   | Pb   | Ni   | Mn   | Al   | Fe   |
|---------|------|------|------|------|------|------|
| Composition | 80.790 | 0.101 | 5.050 | 1.022 | 9.099 | 3.749 |
NAB alloy was melted in an electric furnace, as described in our earlier research work. The as-received NAB alloy was cut into small pieces and was placed in a graphite crucible. The furnace was gradually heated and was held at 1250°C for 30 minutes. The slag formed in the course of melting was removed. The reinforcement CaCO$_3$ (0.20 weight %) was added to melted NAB and stirred mechanically. Sequentially, the melt was poured into a mold (Φ 18mm ×150mm) and was air-cooled.

The microstructure of the developed composite was observed along the cross-section. The specimen was polished as per standard metallographic techniques and was etched using an etchant (solution of 100 ml H$_2$O, 5 ml HCl, and 5 grams FeCl$_3$) for 3 seconds. The micrographs were obtained using a Carl Zeiss microscope. The micro hardness of the developed composite was determined using Mitutoyo Vicker’s micro hardness tester. The specimens were indented at a normal load of 100 g for 15 seconds at ten different regions, and the average micro hardness was reported. Specimens for the tensile test (room temperature and high-temperature) were prepared as outlined by the standard ASTM E8.

The hot-tensile test was performed at 600°C. The Tribological characteristics (dry-sliding condition) of the developed composite were assessed using a pin-on-disk tribometer. The tribology-test specimen preparation and tribology test conduction were in line with the standard ASTM G99. The tribology test parameters are given in table 2.

| Sl. No. | Parameters       | Units | Value |
|---------|------------------|-------|-------|
| 1       | Sliding distance | m     | 1500  |
| 2       | Load             | N     | 20    |
| 3       | Velocity         | m/sec | 2.5   |

3. Results and Discussion

3.1 Microstructure

The base material had a coarse grain structure with Cu-rich α phase, β’-phase, and intermetallic precipitates of κ-phases. The microstructure of the fabricated NAB-0.2CaCO$_3$ composite is shown in Figure 1, which depicts the refinement of the grains, reduction of the β’-phase, and preferential formation of intermetallic precipitates of κ-phases (κ$_{III}$, κ$_{IV}$, and κ$_{IV}$).

![Figure 1. Optical micrograph of (a)Base Metal, NAB-0.2CaCO$_3$ composite at magnification of (b) 200x; (c) 500x](image)

The microstructural evolution is attributed to the presence of CaCO$_3$ that dissociates as CaO and CO$_2$ at around 825°C. CaO is a ceramic phase and acted as potential sites for heterogeneous nucleation, and in turn, acted as a grain-pinning agent. This enabled refinement of microstructure in the NAB-CaCO$_3$...
composite. The fine dispersion of CaO is evident from the microstructural analysis. The high-resolution scanning electron micrograph of NAB-0.2CaCO$_3$ composite depicting the phases is shown in figure 2.

![High-resolution scanning electron micrograph of NAB-0.2CaCO$_3$ composite depicting the phases.](image)

**Figure 2.** High-resolution scanning electron micrograph of NAB-0.2CaCO$_3$ composite depicting the phases.

The elemental composition of the developed composite was determined using energy-dispersive X-ray spectroscopy (EDS). The chosen area for the EDS analysis and the EDS graph is shown in Figure 3 (a) and Figure 3 (b) respectively. The elemental composition analysis confirmed the presence of the following elements in the developed composite: Cu, Ni, Al, Fe, Ca, and O. The XRD graph is shown in Figure 3 (c). The XRD analysis confirmed the normal phases of NAB alloy and CaO in the developed composite. No new intermetallic phases were observed.

![Chosen area for EDS analysis; EDS graph; XRD graph](image)

**Figure 3.** a) Chosen area for EDS analysis; b) EDS graph; c) XRD graph

3.2 Micro hardness

The average micro hardness of the as-cast base material was 210 HV. The microstructural refinement and presence of hard ceramic phase CaO in the developed composite resulted in an average micro
hardness of 350 HV. The micro hardness was two and a half times higher than that of the base material. The results are shown in Table 3.

### Table 3. Hardness of the developed composite

| Sample | 1 | 2 | 3 | 4 | 5 |
|--------|---|---|---|---|---|
| Hardness (HV) | 330 | 362 | 345 | 338 | 375 |

#### 3.3 Tensile Strength

The average tensile strength of the base material was 338 MPa. The developed composite exhibited an average tensile strength of 370 MPa, which was ~10% higher than that of the base material. The grain refinement augmented the tensile strength of the developed composite. The results are shown in Table 4.

### Table 4. Tensile strength of the developed composite

| Sample | 1 | 2 | 3 | 4 | 5 |
|--------|---|---|---|---|---|
| Tensile Strength (MPa) | 352 | 370 | 393 | 367 | 368 |

#### 3.4 Hot Tensile Strength

The conventional NAB alloy had an average hot-tensile strength of 94 MPa at 538°C [24]. The developed composite was subjected to hot-tensile test at 600°C. The average hot-tensile strength was 127 MPa. The results indicate that the hot-tensile strength of the developed composite is higher than that of the conventional NAB alloy. The results are shown in Table 5.

### Table 5. Hot Tensile Strength of the developed composite

| Sample | 1 | 2 | 3 | 4 | 5 |
|--------|---|---|---|---|---|
| Hot-Tensile Strength (MPa) at 600°C | 127 | 120 | 124 | 127 | 137 |

#### 3.5 Wear Rate

The wear rate of the base material and the developed composite was determined using a pin-on-disc tribometer. The wear rate of the base material was $13.03 \times 10^{-4}$ mm$^3$/m and that of the developed composite was $10.08 \times 10^{-4}$ mm$^3$/m. The results explicit the improvement in wear resistance by 29%. The results are shown in Table 6.

### Table 6. Wear rate of the developed composite

| Sample | 1 | 2 | 3 | 4 | 5 |
|--------|---|---|---|---|---|
| Wear Rate ($\times 10^{-4}$ mm$^3$/m.) | 10.1 | 10.3 | 9.8 | 10.1 | 10.1 |

#### 4. Conclusion

NAB alloy was composited with 0.2%CaCO$_3$ successfully. The results demonstrated the following:

- Microstructural analysis confirms fine dispersion of CaO, refinement of the grains, reduction of the β'-phase, and preferential formation of intermetallic precipitates of κ-phases (κ$_{II}$, κ$_{III}$, and κ$_{IV}$) in NAB-0.2%CaCO$_3$
- The microstructural refinement enabled an increase in microhardness (2.5 times), tensile strength (~10%), hot-tensile strength, and wear resistance (~29%) of the NAB-0.2%CaCO$_3$ than that of the base material.

#### Reference

[1] Czytyrca E 2000 Fatigue Crack Growth Thresholds, Endurance Limits, and Design: ASTM International

[2] Luo Q, Qin Z, Wu Z, Shen B, Liu L and Hu W 2018 The corrosion behavior of Ni-Cu gradient layer on the nickel aluminum-bronze (NAB) alloy Corrosion Science 138 8-19
[3] Shankar K V and Sellamuthu R 2016 An investigation on the effect of nickel content on the wear behaviour and mechanical properties of spinodal bronze alloy cast in metal mould International Journal of Materials Engineering Innovation 7 89-103
[4] Thossatheppitak B, Suranuntchai S, Uthaisangsuk V, Manonukul A and Mungsuntisuk P 2013 Mechanical properties at high temperatures and microstructures of a nickel aluminum bronze alloy. In: Advanced Materials Research: Trans Tech Publ) 82-9
[5] Yamatogi T, Murayama H, Uzawa K, Mishima T and Ishihara Y 2011 Study on Composite Material Marine Propellers マリンエンジニアリング 46 330-40
[6] Ilangovan S, Vignesh R V, Padmanaban R and Gokulachandran J 2019 Effect of composition and aging time on hardness and wear behavior of Cu-Ni-Sn spinodal alloy Journal of Central South University 26 2634-42
[7] Carlton J 2018 Marine propellers and propulsion: Butterworth-Heinemann)
[8] Yamatogi T, Murayama H, Uzawa K, Kageyama K and Watanabe N 2009 Study on cavitation erosion of composite materials for marine propeller. In: Seventeenth International Conference on Composite Materials (ICCM17), Edinburgh, UK, July, 27-31
[9] Lv Y, Wang L, Xu X and Lu W 2015 Effect of post heat treatment on the microstructure and microhardness of friction stir processed NiAl Bronze (NAB) alloy Metals 5 1695-703
[10] Michels H T and Kain R M 2003 Effect of Composition and Microstructure on the Seawater Corrosion Resistance of Nickel Aluminum Bronze. In: CORROSION 2003: NACE International)
[11] Qin Z, Zhang Q, Luo Q, Wu Z, Shen B, Liu L and Hu W 2018 Microstructure design to improve the corrosion and cavitation corrosion resistance of a nickel-aluminum bronze Corrosion Science 139 255-66
[12] Wang C, Jiang C, Chai Z, Chen M, Wang L and Ji V 2017 Estimation of microstructure and corrosion properties of peened nickel aluminum bronze Surface and Coatings Technology 313 136-42
[13] Wu Z, Cheng Y F, Liu L, Lv W and Hu W 2015 Effect of heat treatment on microstructure evolution and erosion–corrosion behavior of a nickel–aluminum bronze alloy in chloride solution Corrosion Science 98 260-70
[14] Qin Z, Wu Z, Zen X, Luo Q, Liu L, Lu W and Hu W 2016 Improving corrosion resistance of a nickel-aluminum bronze alloy via nickel ion implantation Corrosion 72 1269-80
[15] Abbasi-Khazaei B and Keshavarz S 2017 Nickel-aluminum-bronze/Al2O3 surface nanocomposite produced by friction-stir processing: Corrosion properties and microstructure Materials and Corrosion 68 883-91
[16] Ilangovan S and Sellamuthu R 2012 An investigation of the effect of Ni content and hardness on the wear behaviour of sand cast Cu–Ni–Sn alloys International Journal of Microstructure and Materials Properties 7 316-28
[17] Ilangovan S, Vignesh R V, Padmanaban R and Gokulachandran J 2018 Progress in Computing, Analytics and Networking: Springer) 559-71
[18] Nair S, Sellamuthu R and Saravanan R 2018 Effect of Nickel content on hardness and wear rate of surface modified cast aluminum bronze alloy Materials Today: Proceedings 5 6617-25
[19] Thapliyal S and 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 30-8
[20] Venkatesan S, Jerald J, Asokan P and Harichandran R 2020 A study on the mechanical and corrosion behaviour of bronze–TiB2 metal matrix composites Materials Today: Proceedings
[21] Zhai W, Lu W, Zhang P, Wang J, Liu X and Zhou L 2018 Wear-triggered self-healing behavior on the surface of nanocrystalline nickel aluminum bronze/Ti3SiC2 composites Applied Surface Science 436 1038-49