Interfacial Microstructure and Bonding Area of Sn-based Alloy-GG25 Gray Iron Bimetallic Material Using Flux, Sn, and Sn-Zn Interlayer Compound Casting

Naglaa Fathy
Department of Physics
College of Science
University of Hail
Hail, Saudi Arabia
naglaaf2002@yahoo.com

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Abstract-A bimetallic casting consisting of GG25 gray iron substrate and Sn-based alloy using the liquid-solid technique has been studied in this paper. Three different pretreatment processes of gray iron surface substrates including flux only, flux and Sn powder, and flux and Sn-8.8% Zn powder eutectic alloy surface treatment were adopted for the aim of improving the quality of tinning, the interfacial structure, and the bonding area of the Sn-based alloy/gray iron bimetallic composite in order to promote the bonding quality of bimetallic castings. Microstructure characterization on the bonding interface was conducted. The novel tinning material for gray cast iron substrate comprising of Sn-8.8% Zn eutectic alloy powder in combination with flux interlayer improved the bonding area, the interfacial bimetal structure, and the shear stress. This improvement is due to the higher interface reaction of Zn with Fe that leads to the formation of a very thin layer of Fe-Zn and Fe-Sn intermetallic phases.

Keywords-Sn-based alloy; GG25 gray iron; flux; Sn-Zn; bimetal; interface

I. INTRODUCTION

Nowadays, manufacturing techniques are more focused on fabricating materials of superior properties and the facilitation of their fabrication techniques. Despite the intensive development of cast metal's structure and properties, the possibilities of the existing monometallic alloys are practically exhausted for fabricating new materials of superior properties [1-3]. Liquid-solid compound casting has been used to fabricate different ferrous and nonferrous functionally graded materials, and is considered the most economical fabrication process, which allows the fabrication of bimetal materials directly [4-8]. For bimetallic bearing materials, higher bonding strength is still required to meet the industrial application demands. More effort on the enhancements of the bimetallic composites interfacial structures and bonding area should be considered. The tin-based $SnSb_8Cu_3$ alloy is one of the most common bimetallic bearing materials used in thrust bearings with substrate shells. Carbon steel alloys are commonly used as shell substrates in liquid-solid compound casting techniques [8-12]. Although the gray cast iron has unique mechanical properties, it has limited applications in the liquid-solid compound casting as solid shells due to its free graphite flacks. Gray iron is well known as flack graphite iron in which the graphite is present in a matrix of ferrite, pearlite, or ferrite-pearlite. Compared with carbon steel substrates, the relatively higher silicon and carbon content, as well as the production processing parameters of gray iron, make eutectic graphite separate from the molten iron. As solid bimetal shells, grey irons have been used in liquid-solid configuration casting [13, 14]. The interfacial bonding strength of Sn-based alloy/grey iron was investigated for bimetal composites fabricated by centrifugal casting process in [13]. In addition, Al-Si alloy/grey iron bimetallic composite has been fabricated. The optimum shear strength was achieved with the assist of hot dipping of the solid iron in a Zn–0.2 wt. % Bi melt [14].

In the current study, the Sn-Zn eutectic alloy was used due to its physical and mechanical properties. The Sn-Zn eutectic system is a promising candidate for the replacement of Sn-Pb solders due to its melting temperature (198°C), which is very close to the Sn-Pb eutectic alloy melting temperature (183°C), so it is suitable for electronic components without major modifications [15]. In addition, the Sn-8.8% Zn eutectic lower melting temperature is favorable and the cost of production is relatively low compared with other Sn-Ag and Sn-In soldering materials [16]. For the aim of improving the interfacial structure and bonding area of Sn-based alloy/gray iron bimetallic composite, the gray iron surface substrate is prepared using three pretreatment processes. Gray iron surface substrates are treated with flux only, flux + Sn powder, and flux + powder Sn-8.8% Zn eutectic alloy. The proposed Sn-Zn

Corresponding author: Naglaa Fathy

interlayer of Sn-based alloy/GG25 gray iron bimetallic material using the tinning process is considered as an alternative new interlayer material designed for fast, easy, high bonding interface and low-cost surface improvement of the gray iron solid substrate. This newly designed Sn-based alloy/GG25 gray iron with Sn-Zn interlayer is more suitable for bimetallic materials of flat and horizontal solid substrates.

II. EXPERIMENTAL WORK

The Sn-based alloy/GG25 gray iron bimetallic composite specimens were prepared using the liquid-solid compound casting technique. Sn-8.8% Zn interlayer alloy samples were prepared by melting pure Sn (99.97%), and pure Zn (99.95%) in graphite crucibles using an electrical muffle furnace. The alloys were melted 2 times to ensure uniform mixing of the elements. Table I shows the chemical compositions of the Sn-based alloy and the GG25 gray iron substrate used for the Sn-based alloy/GG25 gray iron bimetallic composite fabrication.

TABLE I. CHEMICAL COMPOSITIONS

Chemical composition	C	Si	Mn	Cu	Pb	Sb	Sn	Fe
Sn-based alloy- ASTM B-23- Grade2	-	-	-	3.0-4.0	0.0-0.35	7.0-8.0	Bal	-
G.G 25 gray iron substrate	3.0-3.25	1.85-2.10	0.4-0.7	-	-	-	-	Bal.

Gray iron substrate specimens of solid cylindrical shape of 25.4mm diameter and 5.5mm thickness were cut and ground with up to 800 grades emery papers. The specimens were tinned with pure Sn and with Sn-8.8% Zn alloy. The direct pre-tinning process of the gray iron substrate that involves Sn powder or Sn-Zn alloy and flux mixture has been explained in detail in [17–18]. The current flux is fabricated with a mixture of chemicals listed in Table II mixed with the pure tin or Sn-Zn powders. The Sn to flux ratio is 1:10 (1g of Sn and 10g of flux). The necessity of using flux in the tinning process during bimetal fabrication is to remove the oxides for the sake of allowing the Sn or Sn-Zn to stick directly to the gray iron surface.

TABLE II. FLUX CHEMICAL COMPOSITION WT.% ML

$ZnCl_2$	$NaCl_2$	NH_4Cl	HCl	H_2O
24 gm	6 gm	3gm	1ml	1ml

In order to study the effect of different pretreatments of gray iron surface on the quality of tinning, the interfacial structure and the bonding area of the Sn-based alloy/gray iron bimetal, three groups of specimens were fabricated.

- The first group of Sn-based alloy/gray iron bimetal was produced by pretreated gray iron substrate with flux only.
- The second group was produced by pretreated gray iron substrate with flux + Sn (1g of Sn powder and 8g of flux).
- The third group was produced by pretreated gray iron substrate with flux + Sn -8.8% Zn (1g of Sn-8.8% Zn powder,8g of flux).

During the tinning process, 0.2gm/cm^2 of flux and Sn or Sn-Zn mixture was distributed on the gray iron shell substrate. Then the substrate was placed on a preheated hot plate of 360^{o}C for 3min. After heating, the gray iron was removed from the hot plate and the tinned surface as cleaned using a towel and tap water and left to cool to room temperature. Sn-based alloy with the chemical composition shown in Table I was melted on a hotplate at 370^{o}C and after 30min the crucible of molten metal was removed from the hotplate and was poured onto a ceramic mold that contained a preheated (370^{o}C for 3min) tinned gray iron substrate. The volume of liquid Sn-based alloy to gray iron substrate ratio was kept to 3:1 for all casting groups.

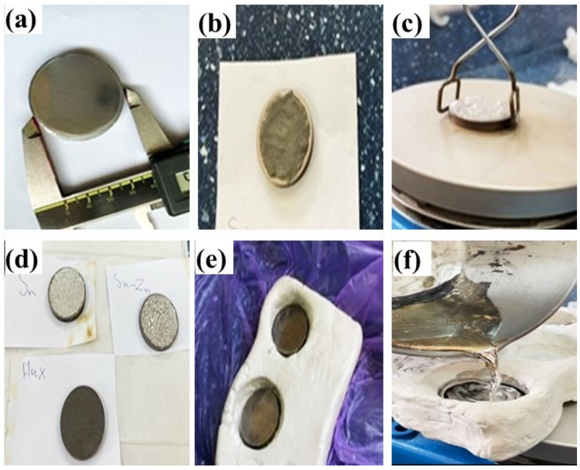

Fig. 1. Sn-based alloy/GG25 gray iron bimetallic casting: (a) gray iron substrate after cutting and grinding, (b)-(c) gray iron substrate during tinning with a hot plate, (d) gray iron substrates after tinning, (e) inserting the tinned gray iron substrate into the ceramic mold, (f) pouring the molten Sn-based alloy onto the ceramic mold.

The microstructure of the Sn-based alloy/gray iron bimetal, especially the interfaces region between the alloy and the gray iron substrate was examined with an Olympus optical microscope with a maximum magnification of 1000X. The optical examination was conducted after grinding, polishing, and etching with 4% nital to define interlayers, lack of bonding, and voids. Measurements of the as-cast specimens of the three groups of the Sn-based alloy/gray iron bimetal composites were taken.

III. RESULTS AND DISCUSSION

A. Macro-and Micro-structures of Base Bimetallic Materials

Figure 2 shows photographs of the Sn-based alloy/GG25 gray iron bimetal composite specimens and the cross section of the three fabricated specimens. Clear and regular bimetal interface for gray iron substrate treated with pure Sn and Sn-8.8% Zn alloy and an irregular bimetal interface for the gray iron substrate treated with flux only were monitored.

Microstructures of the materials used in the fabrication of tin-based alloy/gray cast iron bimetallic composite are shown in Figure 3. Figure 3(a) shows the optical microstructure of Sn-based alloy revealing Cu_6Sn_5 and SnSb phases reinforced in the solid solution of the Sn matrix. The Cu_6Sn_5 phase has the shape of asterisks. The microstructure of a matrix of solid solution with hard-embedded phases of Cu_6Sn_5 and SnSb make a metal matrix composite possessing fatigue-resistant properties [19–21].

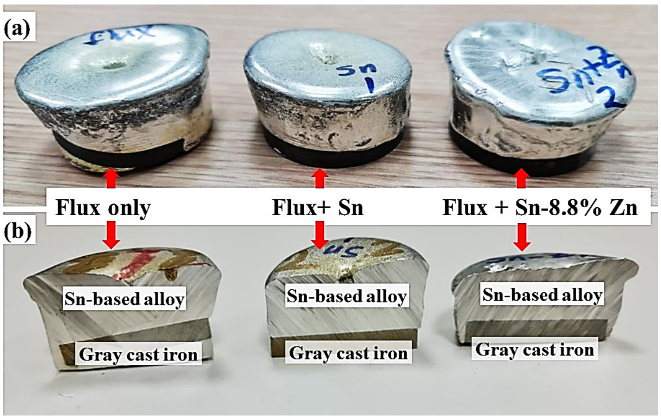

Fig. 2. (a) Sn-based alloy/GG25 gray iron bimetal composite specimens, (b) cross sections of three specimens.

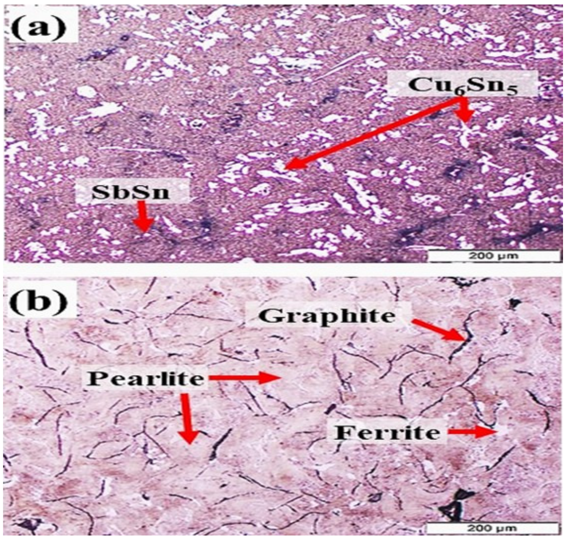

Fig. 3. Microstructures of (a) tin-based Babbitt alloy and (b) gray cast iron substrate, used for preparing the bimetallic casting.

Previous studies [22–24] reported that the variation in the chemical composition of tin-based alloy modifies the microstructure. Tin-based alloys containing less than 8% Sb are characterized by a solid solution with distributed asterisks and needles of Cu_6Sn_5, copper-rich constituents, and fine precipitates of SbSn. On the contrary, the tin-based alloys containing greater than 8% Sb exhibit a primary cuboid phase of SbSn. The microstructure of Sn-based Babbitt alloy acquired in the present study is in good agreement with those available in the literature [22–24]. The microstructure of gray cast iron substrate (Figure 3(b)) shows the three common phases of ferrite, pearlite, and free graphite. The higher percentage of the pearlite verifies the Mn and Cu content in the gray cast iron chemical composition.

B. Microstructures of Interfacial Sn-based Alloy/Gray Cast Iron Bimetallic Composites

The microstructures of the interfaces of bimetallic composites containing tin-based alloy/gray cast iron substrate with different surface pre-treatments of gray cast iron solid substrates are shown in Figure 4. Visual observation of the interfacial microstructures of the bimetallic interface fabricated using flux only shows poor bonding between the two metallic parts (Figure 4(a)). Some small voids were observed in the interface area of bimetal composites fabricated using flux + Sn interlayer (Figure 4(b)). A uniform interfacial bonding free of defects is observed in bimetallic composites fabricated using flux + Sn- 8.8% Zn alloy (Figure 4(c)). Tin-based alloy/gray cast iron composites fabricated with flux + Sn-8.8% Zn alloy revealed a good quality of interfacial bonding compared with other previous gray cast iron pre-treatment conditions. Figure 5 shows the interfacial bonded areas of the three fabricated Sn-based alloy/ gray cast iron bimetallic composites with three different surface pre-treatments of gray cast iron solid substrate. It can be seen that substrate treated with flux only has the lowest value, while the substrate treated with flux + Sn shows comparable results. Gray cast iron substrate treated with flux + Sn-8.8% Zn exhibited a comparatively higher value. Both $FeSn_2$ and FeSn Intermetallic Compounds (IMCs) could be formed in temperatures ranging from 300 to 500°C. Fe-Zn coating grows because of a rather complicated process of atomic diffusion of both metals with the formation of elementary intermetallic bonds and subsequent phase transformations. Layers consisting of these compounds have different compositions and thicknesses. They are usually marked with Greek alphabet letters, i.e. gamma (Γ), gamma1 (Γ1), delta (δ), zeta (ζ), and sometimes eta (η). Individual phases differ significantly not only by composition and morphology of the grain but also by mechanical characteristics. The formation of individual phases in the coating is ruled by the binary phase diagram Fe – Zn shown in [25-27].

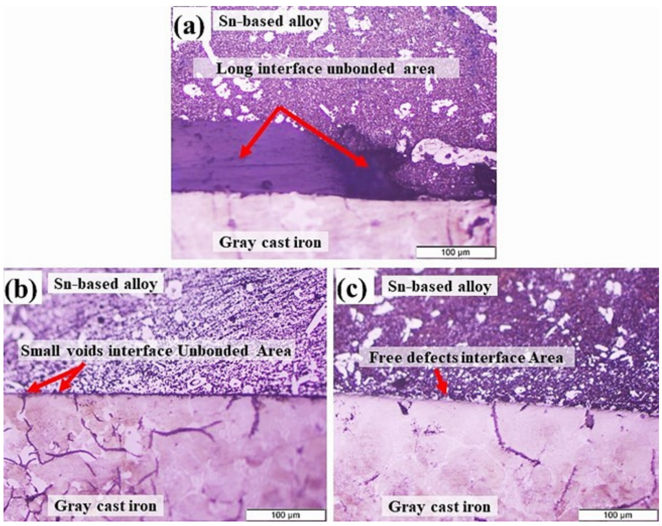

Fig. 4. Optical microstructure interfaces of tin-based alloy/gray cast iron specimens with different interlayer compositions: (a) flux only, (b) flux with Sn, (c) flux with Sn-8.8% Zn alloy.

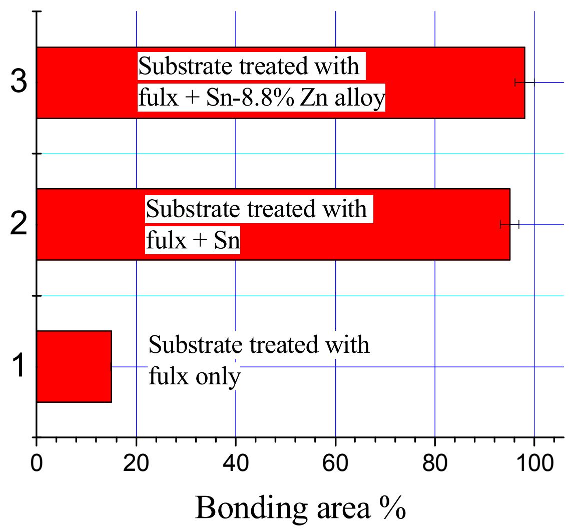

Fig. 5. Sn-based alloy/ gray cast iron bimetallic interfacial bonded areas as a function of interlayer pre-treatment compositions for the 3 sample groups.

C. Mechanical Properties of Sn-based Alloy/Gray Cast Iron Bimetallic Composites

The shear strengths of the Sn-based alloy/GG25 gray iron bimetallic composites with Sn and Sn-8.8% Zn interlayer compositions are shown in Figure 6. The shear strength of the bimetal fabricated with Sn-8.8 % Zn interlayers is significantly more by 20% than the one fabricated with Sn interlayer, which is mainly due to the improvements of the interface bond area of Sn-8.8% Zn interlayers.

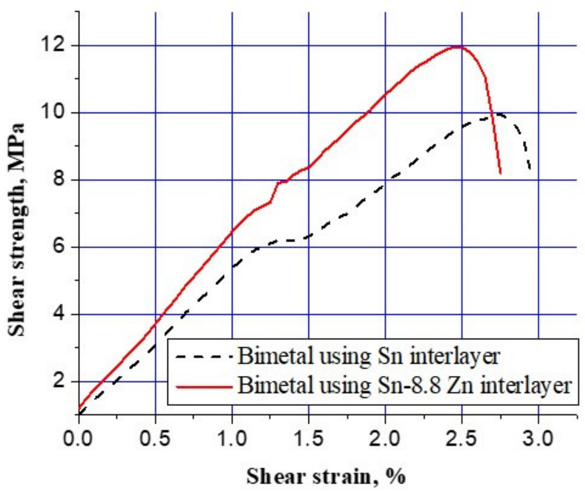

Fig. 6. Shear stress-strain curves of the tin-based alloy/gray cast iron specimens with Sn and Sn-8.8% Zn interlayer compositions.

IV. CONCLUSION

In this paper, bimetallic specimens of Sn-based alloy/gray cast iron were successfully prepared by liquid-solid compound casting after depositing the molten Sn-based alloy on the solid gray cast iron substrate. A novel tinning material for gray cast iron substrate comprising of the Sn-8.8% Zn eutectic alloy powder in combination with flux was performed.

Sn-8.8% Zn eutectic alloy interlayer improved the bonded area and interfacial bimetal structure, due to the higher interface reaction of Zn with Fe that led to the formation of very thin Fe-Zn and Fe-Sn intermetallic phases.

Higher shear stress was achieved using Sn-8.8% Zn interlayer as tinning material. The optimum Zn content in Sn-Zn alloy interlayer should be considered for future work in order to optimize the fabrication of Sn-based alloy/gray cast iron bimetallic composite with high quality and long life bi-metal bonding.

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REFERENCES

[1] M. Ramadan and N. Fathy, "Solidification Microstructure of Rheocast Hyper-Eutectic Al–18Si Alloy," *Journal of Metallurgical Engineering*, vol. 2, no. 4, pp. 149–154, 2013.

[2] M. Ramadan, N. El-Bagoury, N. Fathy, M. A. Waly, and A. A. Nofal, "Microstructure, fluidity, and mechanical properties of semi-solid processed ductile iron," *Journal of Materials Science*, vol. 46, no. 11, pp. 4013–4019, Mar. 2011, https://doi.org/10.1007/s10853-011-5329-7.

[3] S. H. Abro, H. A. Moria, A. Chandio, and A. Z. Al-Khazaal, "Understanding the Effect of Aluminum Addition on the Forming of Second Phase Particles on Grain Growth of Micro-Alloyed Steel," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5153–5156, Feb. 2020, https://doi.org/10.48084/etasr.3243.

[4] J. Gawronski, J. Szajnar, and P. Wrobel, "Study on theoretical bases of receiving composite alloy layers on surface of cast steel castings," *Journal of Materials Processing Technology*, vol. 157–158, pp. 679–682, Sep. 2004, https://doi.org/10.1016/j.jmatprotec.2004.07.153.

[5] N. Fathy and M. Ramadan, "Influence of volume ratio of liquid to solid and low pouring temperature on interface structure of cast Babbitt-steel bimetal composite," *AIP Conference Proceedings*, vol. 1966, no. 1, Feb. 2018, Art. no. 020028, https://doi.org/10.1063/1.5038707.

[6] R. K. Tayal, S. Kumar, V. Singh, A. Gupta, and D. Ujjawal, "Experimental Investigation and Evaluation of Joint Strength of A356/Mg Bimetallic Fabricated Using Compound Casting Process," *International Journal of Metalcasting*, vol. 13, no. 3, pp. 686–699, Apr. 2019, https://doi.org/10.1007/s40962-018-0288-2.

[7] M. Ramadan, K. S. A. Halim, A. S. Alghamdi, A. Khaliq, and N. Fathy, "An Empirical Model for Carbon Diffusion in Grey Iron/Stainless Steel Bimetallic Composites Incorporating Eutectic Carbides," *International Journal of Metalcasting*, vol. 15, no. 4, pp. 1375–1384, Jul. 2021, https://doi.org/10.1007/s40962-020-00561-9.

[8] Yu. I. Veslopolov and I. Yu. Veslopolov, "Microstructure of the babbitt B83 and its melting zone with a bearing steel," *Metal Science and Heat Treatment*, vol. 34, no. 11, pp. 708–710, Aug. 1992, https://doi.org/10.1007/BF00712430.

[9] N. Fathy, "Interface Microstructure Investigation of Babbitt-Carbon Steel Composite Using Flux with Glycerol and Petroleum Jelly Additives," *Engineering, Technology & Applied Science Research*, vol. 8, no. 3, pp. 3028–3031, Jun. 2018, https://doi.org/10.48084/etasr.2071.

[10] M. Ramadan, N. Fathy, K. Abdel-Halim, and A. Alghamdi, "New trends and advances in bi-metal casting technologies," *International Journal of Advanced and Applied Sciences*, vol. 6, no. 2, pp. 75–80, Oct. 2019, https://doi.org/10.21833/ijaas.2019.02.011.

[11] M. Ramadan, "Interface Structure and Elements Diffusion of As-Cast and Annealed Ductile Iron/Stainless Steel Bimetal Castings,"

Engineering, Technology & Applied Science Research, vol. 8, no. 2, pp. 2709–2714, Apr. 2018, https://doi.org/10.48084/etasr.1856.

[12] M. Cholewa, T. Wrobel, and S. Tenerowicz, "Bimetallic layer castings," *Journal of Achievements in Materials and Manufacturing Engineering*, vol. 43, no. 1, pp. 385–392, 2010.

[13] P. Diouf and A. Jones, "Investigation of Bond Strength in Centrifugal Lining of Babbitt on Cast Iron," *Metallurgical and Materials Transactions A*, vol. 41, no. 3, pp. 603–609, Nov. 2010, https://doi.org/10.1007/s11661-009-0112-y.

[14] Z. Guo, M. Liu, X. Bian, M. Liu, and J. Li, "An Al–7Si alloy/cast iron bimetallic composite with super-high shear strength," *Journal of Materials Research and Technology*, vol. 8, no. 3, pp. 3126–3136, Feb. 2019, https://doi.org/10.1016/j.jmrt.2017.06.014.

[15] K. Suganuma, K. Niihara, T. Shoutoku, and Y. Nakamura, "Wetting and interface microstructure between Sn–Zn binary alloys and Cu," *Journal of Materials Research*, vol. 13, no. 10, pp. 2859–2865, Jul. 1998, https://doi.org/10.1557/JMR.1998.0391.

[16] C. M. L. Wu, C. M. T. Law, D. Q. Yu, and L. Wang, "The wettability and microstructure of Sn-Zn-RE alloys," *Journal of Electronic Materials*, vol. 32, no. 2, pp. 63–69, Oct. 2003, https://doi.org/10.1007/s11664-003-0238-4.

[17] M. Ramadan, B. Ayadi, W. Rajhi, and A. S. Alghamdi, "Influence of Tinning Material on Interfacial Microstructures and Mechanical Properties of Al12Sn4Si1Cu /Carbon Steel Bimetallic Castings for Bearing Applications," *Key Engineering Materials*, vol. 835, pp. 108–114, 2020, https://doi.org/10.4028/www.scientific.net/KEM.835.108.

[18] M. Ramadan, A. S. Alghamdi, K. M. Hafez, T. Subhani, and K. S. Abdel Halim, "Development and Optimization of Tin/Flux Mixture for Direct Tinning and Interfacial Bonding in Aluminum/Steel Bimetallic Compound Casting," *Materials*, vol. 13, no. 24, Jan. 2020, Art. no. 5642, https://doi.org/10.3390/ma13245642.

[19] J. Koutsky and J. Vesela, "Evaluation of white metal adhesion (conventional casting and thermal wire arc spraying) by ultrasonic non-destructive method," *Journal of Materials Processing Technology*, vol. 157–158, pp. 724–728, Sep. 2004, https://doi.org/10.1016/j.jmatprotec.2004.07.131.

[20] N. P. Barykin, F. A. Sadykov, and I. R. Aslanian, "Wear and failure of babbit bushes in steam turbine sliding bearings," *Journal of Materials Engineering and Performance*, vol. 9, no. 1, pp. 110–115, Oct. 2000, https://doi.org/10.1361/105994900770346367.

[21] F. A. Sadykov, N. P. Barykin, I. Sh. Valeev, and V. N. Danilenko, "Influence of the structural state on mechanical behavior of tin babbit," *Journal of Materials Engineering and Performance*, vol. 12, no. 1, pp. 29–36, Oct. 2003, https://doi.org/10.1361/105994903770343448.

[22] R. R. Dean and C. J. Evans, "Plain bearing materials: The role of tin," *Tribology International*, vol. 9, no. 3, pp. 101–108, Mar. 1976, https://doi.org/10.1016/0301-679X(76)90032-3.

[23] G. C. Pratt, "Materials for Plain Bearings," *International Metallurgical Reviews*, vol. 18, no. 2, pp. 62–88, Mar. 1973, https://doi.org/10.1179/imtlr.1973.18.2.62.

[24] M. Moazami Goudarzi, S. A. Jenabali Jahromi, and A. Nazarboland, "Investigation of characteristics of tin-based white metals as a bearing material," *Materials & Design*, vol. 30, no. 6, pp. 2283–2288, Mar. 2009, https://doi.org/10.1016/j.matdes.2008.07.056.

[25] M. Singh and S. Bhan, "Contribution to the Fe—Sn system," *Journal of Materials Science Letters*, vol. 5, no. 7, pp. 733–735, Apr. 1986, https://doi.org/10.1007/BF01730231.

[26] K. Han, I. Ohnuma, K. Okuda, and R. Kainuma, "Experimental determination of phase diagram in the Zn-Fe binary system," *Journal of Alloys and Compounds*, vol. 737, pp. 490–504, Nov. 2018, https://doi.org/10.1016/j.jallcom.2017.11.320.

[27] L. Zhu, S. Honrao, B. Rijal, R. G. Hennig, and M. V. Manuel, "Phase equilibria and diffusion coefficients in the Fe-Zn binary system," *Materials & Design*, vol. 188, Nov. 2020, Art. no. 108437, https://doi.org/10.1016/j.matdes.2019.108437.