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RESEARCH PAPER

BONDING OF INTERFACE BIMETAL ALUMINUM-BRONZE FOR BIMETAL BUSHING PRODUCED BY SOLID LIQUID METHOD

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ABSTRACT

Bimetal is a combination of two dissimilar metals that form a metallurgical bond. The manufacture of bimetallic bushing by centrifugal casting using the solid-liquid method has not been widely developed. There is still not recommendation for rotational speed or optimum temperature used in the manufacture of bimetallic bushing. This main objective of this research was to determine the first frozen layer temperature of the aluminum-silicon alloy when bronze was poured in centrifugal casting to produce a well-integrated bond interface. The materials used were aluminum-silicon alloy and bronze. The molten temperature of aluminum-silicon alloy used was 725°C, while bronze was set up at a temperature of 1100°C. Molten metal was pouring into the mold alternately. First, aluminum-silicon alloy was poured into the mold. Then, bronze was poured gradually to form a bushing aluminum alloy-bronze bimetallic. The temperature variations of the first frozen layer of aluminum-silicon alloy were 27ºC, 350ºC, 400ºC, and 450ºC when bronze poured. The molten metal was poured with the filling speed of about 0.2 kg/s into a rotating sand mold. The rotational speed of the mold was 350 rpm. The result shows that the bond interface's width increases as the first frozen layer aluminum-silicon alloy temperature increases. As a result, interface wear and hardness are increased compared to the base metal. Hence, centrifugal casting with the first frozen layer aluminum-silicon alloy was 450ºC recommended for aluminum alloy-bronze bimetal bushing applications.

Keywords: Bimetal, Interface, Centrifugal casting; Aluminum alloy-bronze

INTRODUCTION

The centrifugal casting principle applies forces generated from the centrifugal acceleration of a rotating mold [1]. Centrifugal casting manufactures a component with limited gas porosity and precise dimensions [1,2]. These characteristics are affected by the high-pressure distribution of molten metal into the mold cavity. The high pressure is caused by forces resulted from the centripetal acceleration of a mold rotation. Furthermore, the centrifugal force in molten metal is influenced by the radius, rotational speed, metal density [1], and gating system [3]. The non-pressurized casting system, with the increase of cross-sectional area towards the mold cavity and the reduce of turbulence, can rise the mechanical properties [4]. Moreover, enlarging the vortex runner diameter in the gating system can increase the bending strength [5]. The porosity is affected by the pressure distribution, which is controlled by rotational speed. Then, adjusting the rotational speed of more than 180 rpm can reduce the porosity [6]. The proper combination of the runner design, rotational speed, and gating system can produce a good quality of casting products [7,8].
Bimetal manufacturing technology is continuously being developed to find the required superior properties. Bimetal is a composite that combines two metals by forming a metallurgical bond [9]. The purpose of bimetal production is to make a component consisting of two metals that have different mechanical properties from the constituent metals. However, the alloyed metal still has its unique properties [10]. Bimetal casting was developed in order to obtain a product that is cheap and easy to produce. In addition, efforts to improve the interfacial bonding of the fused metal pairs are still developed continuously [11]. This improvement is aimed to make an equality between bimetal casting and conventional casting technology. The strength of the metallic bond on the surface of the two metals improves the mechanical properties of the components. The two alloyed metals complement each other in their physical, mechanical, and chemical properties [12].
Bimetal can be manufactured by centrifugal casting [10] or gravity casting [13]. The manufactured by casting forms a metallurgical bonding at the interface and diffusion of the two metals during pouring, which results a high-strength bond [14]. One of the bimetallic applications currently being developed is the manufacture of bushing products. The bushings have a low density caused by cast defects [13] when manufactured by gravity casting. The bushings made with centrifugal casting will obtain products with less porosity, smoother surfaces, precision dimensions, and faster solidification [2].
Centrifugal casting utilizes the centrifugal force generated by a rotating mold to distribute the molten metal into the mold [1]. High rotation will produce high pressure, so that reduce the defects in the product [15]. The high rotation speed can avoid sliding defects when pouring molten metal. The surface of the casting becomes rough, and gas porosity appears if the casting is carried out at low temperatures. Pouring temperature affects the amount of segregation and freezing rate [10].
The Chornief equation can be used to calculate the first layer freezing time at the aluminum-bronze of the bimetallic interface [10]. The pouring of the second molten metal with a different temperature will change the characteristics of the metallurgical

bond at the interface. Diffusion ability and interface hardness of the bimetal depend on the temperature of the first frozen layer of aluminum when bronze is poured into the mold. Higher pouring temperatures increase intermetallic bonding at the interface. In addition, metal oxides will decrease if the temperature of the first frozen layer is higher [10]. The delay in pouring the molten bronze after the first frozen layer also causes defects in the bimetallic interface. This causes diffusion, and metallurgical bonds at the interface are not formed properly [9].
The strength of the interface bond in the aluminum-bronze bimetal increases in line with the increase of the first frozen layer temperature aluminum during pouring. The strength at the interface is resulted from the bonding of the intermetallic and intermolecular compounds of the two metals being held together. However, a new brittle phase can appear if the pouring temperature is too high [10]. As a result, it can reduce the strength of the bimetal. The increase of the rotational speed during pouring also increases the interfacial bond strength among metals in centrifugal casting [9]. This enhancement is caused by the high pressure that encourages the formation of a better bond at the interface. The example of bonds formed at the interface is the intermetallic and quasicrystalline phases embedded in the Al-FCC matrix. The quasicrystalline phase is stable and has high mechanical strength (4-7 times than before) [16]. The physical, mechanical, and chemical properties of the intermetallic phase differ from those of the two constituent metals.
The technology, process, and method for the manufacture of bimetallic bushings by centrifugal casting are continuously being developed, but the recommended first frozen layer temperature does not yet exist. Analysis of microstructure, hardness, and wear resistance were carried out on the aluminum-bronze metal interface. This research was conducted to determine the temperature of the first frozen layer in centrifugal casting in order to produce a suitable integration at the bimetal aluminum-bronze interface.

MATERIAL AND METHODS

The main materials used in this study were aluminum-silicon alloy and bronze. The compositions of aluminum-silicon alloy and bronze (20 wt% Cu) were shown at **Table 1** (tested by SEM-EDS Quanta x50 SEM Series). The main composition of aluminum-silicon alloy was in-line with the previous study [17]. The Properties of bronze (20%Cu) [18] and aluminum-silicon alloy [19] were shown at **Table 2.**

Table 1 The main chemical composition of materials (wt.%)

Alloy	Composition (wt.%)					
	Al	Cu	Si	Sn	Fe	C
Bronze	-	79.33	-	20.76	-	0.89
Aluminum-silicon alloy	74.82	1.91	13.96	-	1.92	7.07

Table 2 Properties of bronze (20%Cu) and aluminum-silicon alloy

Alloy	Properties		
	ρ (kg.m^{-3})	σ (UTS) (MPa)	Hardness (HVN)
Bronze (20%Cu)	8842	219	305
Aluminum-silicon alloy (4032)	2680	317	125

Aluminum alloy-bronze bimetallic bushing was manufactured by centrifugal casting with a solid-liquid method. The melting temperature of aluminium-silicon alloy was 725ºC, while bronze was melted at a temperature of 1100ºC. The molten metal was poured with a constant filling speed of about 0.2 kg/s into a rotating sand mold. First, aluminium-silicon alloy was poured into the mold. Then, bronze was poured gradually to form a bushing aluminium alloy-bronze bimetallic. The temperature variations of the first frozen layer of aluminium-silicon alloy were 27ºC, 350ºC, 400ºC, and 450ºC, when bronze poured. The schematic product of bimetallic bushing was described clearly in **Fig. 1**. Bushings had 35 mm for outer and 25 mm for inner diameters, with 30 mm of height. The thickness of both aluminium-silicon alloy and bronze is 2.5 mm.

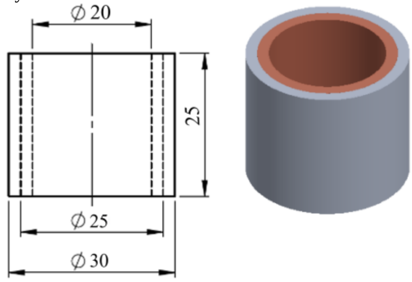


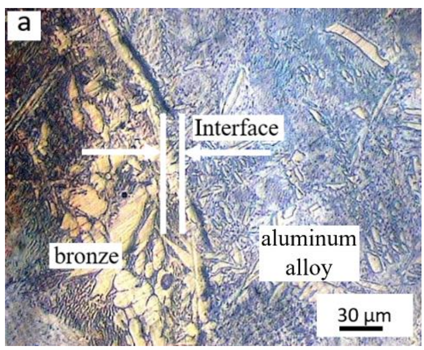
Fig. 1 The schematic product of bimetallic bushing

The observations done in this study included microstructures in the bond interface of bimetal. The microstructure characterization was analyzed using SEM-EDS (Quanta x50 SEM Series) and a metallurgical microscope (PME 3, Olympus, Japan). Preparation was carried out using #180 to #1500 sandpapers to get a smooth surface, then polished by autosol. HNO_3 60% was used in bronze, while hidroflouride (HF) 65% was used in aluminum-silicon alloy to uncover the microstructure (etching process).
The tests carried out in this study were hardness and wear. A hardness micro vickers tester (HMV-M3, Shimadzu, Japan) was used to obtain the hardness in the bond interface between aluminum-silicon alloy and bronze samples. The distance between each test point of the hardness test was 100 µm with a load of 200 gf then hold for 5s. The wear test was done on the bond interface between aluminum-silicon alloy and bronze samples using universal wear (Riken Ogoshi's, Tokyo, Japan) with a load of 6.36 kgf as far as 15 m.

RESULTS AND DISCUSSION

Results

The result of the microstructure observation at the bond interface with variations in the first frozen layer temperature of aluminum-silicon alloy can be seen in **Fig. 2**. Based on observations, aluminum alloy-bronze intermetallic compounds (IMCs) occur in all products with variations in the temperature of the first frozen layer. It is similar with previous research about Al-Cu bimetal [10, 20, 21]. The thickness of IMCs increases in line with



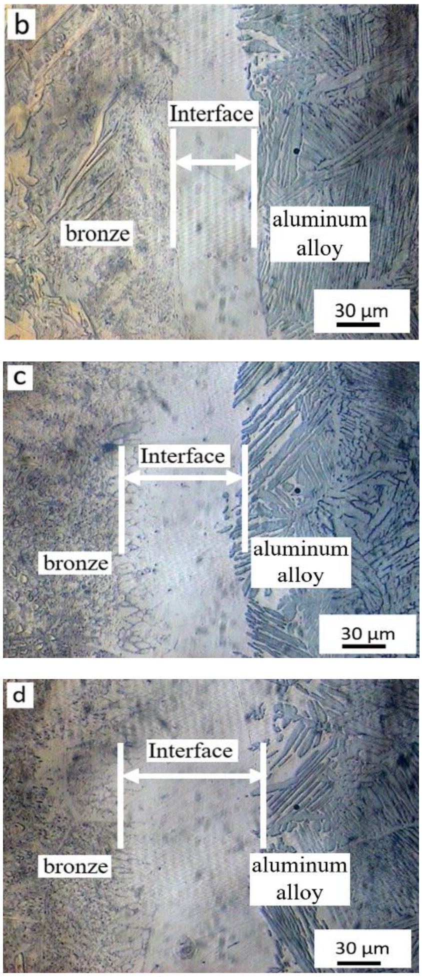


Fig. 2 The bimetal interface microstructure of aluminum alloy-bronze, produced by the first frozen layer of aluminum-silicon alloy with the temperature variations of 27ºC (a), 350ºC (b), 400ºC (c) and 450ºC (d).

the increase of the first frozen layer temperature. The thicknesses of IMCs for the products with the temperature of 27ºC, 350ºC, 400ºC, and 450ºC are 10 µm, 54 µm, 83 µm, and 96 µm, respectively.

There is a significant difference in layers found in the interface microstructure observation**. Fig. 3(a)** shows the microstructure at the bond interface with the interface layer between aluminum-silicon alloy and bronze (based on SEM-EDS). Based on the observation, there are three layers formed, namely interface bronze (layer B), interface, and interface aluminum-silicon alloy (layer A). The results of this observation are similar with previous research [20, 21]. Microstructure of a biphasic aluminum bronze alloy with equilibrium cooling contains of a light grain (α phasa) and a dark grain. This structure is resulted from the equilibrium transformation of β at rates lower than 10°C/min, which transformed by eutectoid reaction at 565°C into lamellar structure [25].

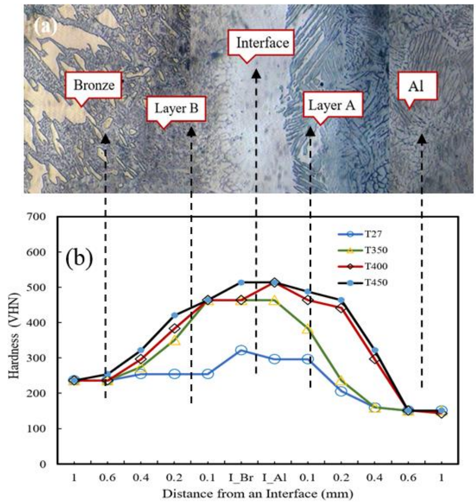


Fig. 3 The microstructure of the interface layer between aluminum-silicon alloy and bronze (a) and the hardness of each interface layer (b)

Table 3 Chemical composition of each layers (wt.%)

Layers	Composition (wt.%)					
	Al	Cu	Si	Sn	Fe	C
Bronze	-	79.33	-	20.76	-	0.89
Layer B	2.93	74.26	2.10	19.11	-	0.83
Interface	5.15	69.88	3.25	20.59	-	0.91
Layer A	60.12	13.24	12.58	5.23	1.02	7.25
Al	74.82	1.91	13.96	-	1.92	7.37

Table 3 shows the main compositions of each layer. The composition in the interface contains combination elements from the composition of aluminum-silicon alloy and bronze, which consists of Al, Cu, Si, and Sn. The width of interface bronze (layer B) and interface aluminum-silicon alloy (layer A) region is almost the same for about 80 µm. In contrast, the width of the interface gets longer as the temperature of the first frozen layer increase. The width range of the interface is between 10 µm until 96 µm.

Moreover, there is also a trend of hardness found in all interface layers. **Fig. 3 (b)** shows the hardness test results in the bond interface region. The hardness of the bond interface is increased compared to the hardness of the base metal. The hardness trend of all specimens is almost similar in all temperature variations of the first frozen layer. The trend of hardness looks similar among specimens with temperature variations in the first frozen layer. The hardness is particularly influenced by the kind of phase of the microstructure [22] and interference component. The highest hardness occurred in products with a first frozen layer temperature of 450°C. The hardness of the aluminum-silicon alloy at 150 VHN was relatively stable and then increased at the interface to 500 VHN, then gradually decreased to 220 VHN in bronze.

The wear of the interface layer shows the lowest among all of the layers. The description of the bimetal bond interface wear is shown in **Fig. 4**. The wear of bronze, layer B, interface, layer A and aluminum-silicon alloy are 2.4E-04, 1.6E-04, 1.3E-04, 2.0E-04, and 5.1E-04 mm^3/kg.m, respectively. The wear of interface is 1.7 times higher than aluminum-silicon alloy and 6.8 times higher than bronze.

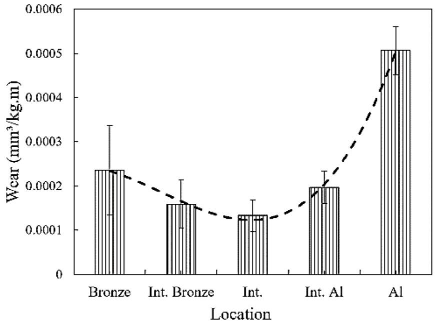


Fig. 4 The wear of bimetal interface of aluminum alloy-bronze

Discussion

The aluminum alloy-bronze bimetal of interface bonding occurs well in the product made by centrifugal casting in all temperature variations of the first frozen layer. The interface width rises in line with the increase of the first frozen layer temperature. The bimetallic interface widths made with the temperature of 27ºC, 350ºC, 400ºC, and 450ºC are 10 µm, 54 µm, 83 µm, and 96 µm, respectively.

The increase of molten metal pressure happens due to the tangential and centrifugal force represents on molten metal when entering the mold [3,23]. The driving force of the molten metal increases due to the high rotation during the pouring process. This condition leads to a better bonding resulted at the interface. The bonding among atoms makes the interfaces formed. However, no new phases are formed [10].

The appropriate temperature of the first frozen layer causes the formation of bonds at the aluminum alloy-bronze metal interface. In addition, the centrifugal force generated by the rotation of the mold pushes the molten metal as it enters the mold [3,23]. Both of these parameters increase the bond strength and diffusion at the interface. Bonds between atoms occur at the interface, but no new phase is formed [10].

Based on the observation of the microstructure, it can be seen that metallurgical bonding occurs strongly. There is no visible impurity at the interface caused by metal oxides and protective oxides of the two materials. There are correlations between mechanical properties and microstructure [24]. The pressure of the molten metal due to the centrifugal force of the first frozen layer temperature is able to remove metal oxides, resulting in metallurgical bonding at the interface. If there is an impurity, the surfaces of the two metals will separate so that a diffusion bonding will not form between them. The force due to the rotation of the mold during poured increases the pressure of the liquid distributed into the mold [1]. This condition reduces the number of defects [15], one of which is oxide impurities.

The hardness in the interface is higher than in the base metals. The hardness at a distance of 0.6 mm from the interface is similar to the hardness of the base metal. The hardness at the bronze interface (layer B) increases to 463 VHN (≥ 1.9 times the base metal of bronze). The interface hardness increased to 513 VHN (≥ 3.3 times base metal of aluminum-silicon alloy and ≥ 2.1 times base metal of bronze). Meanwhile, the aluminum interface hardness (layer A) increased to 487 VHN (≥ 3.2 times the base metal of aluminum-silicon alloy). The increase in hardness is due to the diffusion of elements from the base metal in the form of Cu, Sn, Si, and other elements. Diffusion occurs by substitution and interstitial. The higher of the first frozen layer temperature when pouring causes diffusion to occur more easily so that the hardness at the interface is higher. Increased hardness occurs due to the formation of hard aluminum carbides.

Increased wear at the interface is due to the formation of Al_2Cu, AlCu, and Al_4Cu_9 [21]. Al is functioned as the substitutional solid solution in the Cu crystalline lattice, simultaneously provides an improvement in the mechanical strength, including its wear rate. The corrosion resistance is also increase because of the formation of a thin alumina film in the surface of the alloy. Aluminum bronzes with high Aluminum content will have large amounts of the fragile phase γ and would be unsuitable for industrial applications. Therefore Cu-Al alloys with contents higher than 12% wt Al are not used for manufacturing [25]. However, higher hardness does not necessarily result in better wear resistance. Hardness is not always considered a major factor in assessing the wear resistance of a material [26]. There is a correlation between surface topography and wear behavior [26]. However, if the surface topography has almost the same conditions, the wear resistance is determined by the hardness.

Increasing the temperature of the first frozen layer causes the area and interface hardness between the two metals to increase. The wider interface area and higher hardness can increase wear resistance. This is a highly desirable combination of structural materials engineering applications. However, too high a hardness can cause elasticity to decrease and cause crack initiation [27].

CONCLUSIONS

This present study serves a general understanding about the temperature of the first frozen layer in centrifugal casting to produce a suitable integration at the bimetal aluminum alloy-bronze interface. There are some specific conclusions found from the observation. The width of the interface increases in line with the first frozen layer temperature increases during the pouring process. The driving force of the molten metal increases due to the high rotation during the pouring process. This condition leads to a better bonding resulted at the interface. Then, in terms of wear and hardness, there is an increase in the interface compared to the base metal. The increased of wear and hardness at the interface is due to the formation of Al_2Cu, AlCu, and Al_4Cu_9. This study also found that the centrifugal casting with the first frozen layer temperature of aluminum-silicon alloy at 450ºC is recommended for aluminum alloy-bronze bimetal bushing applications. However, in conducting further studies, researchers should consider conducting the tensile, shear, and impact strength tests first to determine the more specific mechanical properties of the interface.

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REFERENCES

1. W.S. Ebhota, A.S. Karun, F.L. Inambao: International Journal of Materials Research, 107(10), 2016, 1-10. https://doi.org/10.3139/146.111423.
2. S. Wu, Q. Xu, X. Xue: Advanced Materials Research, 317-319, 2011, 456-459. https://doi.org/10.4028/www.scientific.net/AMR.317-319.456.
3. L.D. Setyana, M. Mahardika, Sutiyoko, Suyitno: Acta Metallurgica Slovaca. 25(3), 2019, 193-202. https://doi.org/10.12776/ams.v25i3.1315.
4. O. Akinlabi, A. Ayodele: Acta Metallurgica Slovaca, 21(2), 2015, 135-141, https://doi.org/10.12776/ams.v21i2.567.
5. R. Ahmad, M.Y. Hasyim: Archives of Metallurgy and Materials. 56(4), 2011, 991-997. https://doi.org/10.2478/v10172-011-0109-6.

6. Y. Ling, J. Zhou, H. Nan, L. Zhu, Y. Yin: Journal of Materials Processing Technology, 251, 2018, 295-304. https://doi.org/10.1016/j.jmatprotec.2017.08.025.
7. P. Suwankan, N. Sornsuwit, N. Poolthong: Key Engineering Materials, 659, 2015, 647-651. https://doi.org/10.4028/www.scientific.net/KEM.659.647.
8. B.H. Hu, K.K. Tong, X.P. Niu, I. Pinwill: Journal of Materials Processing Technology, 105(1-2), 1999, 128-133. https://doi.org/10.1016/S0924-0136(00)00546-X.
9. S. Pandey, P. Kumar, S.K. Jha, A.K. Bharat: Analysis of Defects for Aluminium Copper Bimetal Fabricated by Centrifugal Casting. ELK Asia Pacific Journals, 2017, 1-6.
10. J. Nazari, M. Yousefi, A. Kerahroodi, B. Mofrad, A. Abhari: International Journal of Materials Lifetime, 1(1), 2015, 20-28. http://pubs.sciepub.com/ijml/1/1/4.
11. M. Ramadan, N. Fathy. N., K.S.A. Halim, A.S. Alghamdi: International Journal of Advanced and Applied Sciences, 6(2), 2019, 75-80. https://doi.org/10.21833/ijaas.2019.02.011.
12. M. Abbasi, J. Hejazi: *The Sixth Annual Seminar of Iranian foundry society*, Iran University of Science and Technology, 1994, 1-15.
13. L. Changyun, W. Haiyan, W. Shiping, X. Lei, W. Kuangfei, F. Hengzhi: Rare Metal Materials and Engineering, 39(3), 2010, 388–392.
14. C. Nerl, M. Wimmer, H. Hoffmann, E. Kaschnitz, F. Langbein, W. Volk: Journal of Materials Processing Technology, 214(7), 2014, 1445-1455. https://doi.org/10.1016/j.jmatprotec.2014.02.018.
15. L. Jia, D. Xu, M. Li, J. Guo, H. Fu: Metals and Materials International, 18(1), 2012, 55–61. https://doi.org/10.1007/s12540-012-0007-0.
16. G.Y. Koga, A.M.B. Silva, W. Wolf, C.S. Kiminamia, C. Bolfarini, W.J. Botta: Journal of Materials Research and Technology, 8(2), 2019, 2092-2097. https://doi.org/10.1016/j.jmrt.2018.12.022.
17. G. Mathers: *The Welding of Aluminium and its Alloys*, Woodhead Publishing, Abington Cambridge, England, 2002. https://doi.org/10.1533/9781855737631.35.
18. S. Slamet, Suyitno, I. Kusumaningtyas, I. M. Miasa: Archives of Foundry Engineering, 1, 2021, 137–145. https://doi.org/10.24425/afe.2021.136090.
19. D. Kopeliovich: *Wrought aluminum-silicon alloy 4032*, 2012. http://www.substech.com/ [access 06.04.2022]
20. W. Jiang, F. Guan, G. Li, H. Jiang, J. Zhu, Z. Fan: Materials and Manufacturing Processes, 34(9), 2019, 1016-1025. https://doi.org/10.1080/10426914.2019.1615084.
21. N. Santoso, B. Suharnadi, B.T. Prayoga, L.D. Setyana: Acta Metallurgica Slovaca, 27(1), 2021, 28-31. https://doi.org/10.36547/ams.27.1.756.
22. S. Darmo, L. D. Setyana, Tarmono, N. Santoso: IOP Conference Series: Materials Science and Engineering, 384, 2018, 1-4. https://doi.org/10.1088/1757-899X/384/1/012017.
23. L.D. Setyana, M. Mahardika, Suyitno: Acta Metallurgica Slovaca, 26(3), 2020, 132-137. https://doi.org/10.36547/ams.26.3.535.
24. R. Bidulský, J. Bidulská, M.A. Grande: Acta Physica Polonica A, 122, 2012, 548-552. https://doi.org/10.12693/APhysPolA.122.548.
25. R. Bidulský, J. Bidulská, F.S. Gobber, T. Kvačkaj, P. Petroušek, M. Actis-Grande, K.-P. Weiss, D. Manfredi: Materials, 13, 2020, 3328. https://doi.org/10.3390/ma13153328.
26. J.A.P.S. Elorz, M.J.Q. Hernández L.F.V. González: Equilibrium Transformations. In: *Solidification and Solid-State Transformations of Metals and Alloys*, Elsevier, Amsterdam, Netherlands, 2017, 209-254. https://doi.org/10.1016/B978-0-12-812607-3.00007-3.
27. R. Bidulský, M.A. Grande, J. Bidulská, T. Kvačkaj, T. Donič: International Journal of Modern Physics B, 24(6,7) 2010, 794-804. https://doi.org/10.1142/S0217979210064435.
28. R. Bidulský, M.A. Grande, J. Bidulská, T. Kvačkaj: Materiali in Tehnologije, 43(6), 2009, 303-308.
29. R. Bidulský, M.A. Grande, E. Dudrova, M. Kabatova, J. Bidulská: Powder Metallurgy, 59, 2016, 121-127. https://doi.org/10.1179/1743290115Y.0000000022.
30. S. Kapoor, K. Januchta, R. E. Youngman, X. Guo, J.C. Mauro, M. Bauchy, S.J. Rzoska, M. Bockowski, M.M. Smedskjaer: Physical Review Materials, 2(6), 2018, 063603. https://doi.org/10.1103/PhysRevMaterials.2.063603.