Vol. 03, Iss. 2 (2025) 250-257, DOI: 10.61552/JME.2025.02.009

JME

Journal of Materials and Engineering

www.jme.aspur.rs

Research article

Mechanical Properties and Microstructure of Al-17Si-2Fe and Al-6.7Si-2Fe functionally Graded Alloys by Sequential Casting

Ali Abbas Hasan[a,*], Abdul Raheem Kadhim Abid Ali[a], Haydar Al-Ethari[a]

[a]*Department of Metallurgical Engineering, Materials Engineering College, University of Babylon, Babylon, Iraq.*

Keywords:

Sequential casting
Aluminum alloy
Interface
Functionally graded
IC pistons

* Corresponding author:

Ali Abbas Hasan
E-mail: mat.abdulraheem.k@uobabylon.edu.iq

Received: 28 June 2024
Revised: 29 July 2024
Accepted: 21 August 2024

ABSTRACT

Internal combustion engines suffer from many problems in their parts due to service, which leads to a decrease in efficiency. This may be due to bade working conditions. One of the important parts is piston. In many applications, it suffers from several problems, including pitting in the piston surface, which leads to the loss of some of its parts and thus leads to failure. It is usually made of aluminum-silicon alloys in different proportions. This research proposed a way to improve the performance of piston by modifying the chemical composition of the alloy and manufacturing method. It was suggested to add iron at a rate of 2% to form a ternary alloy and to manufacture it using the method of graded functional materials through successive casting. This method led to the integration of two alloys into one part where the surface is made of Al-17Si-2Fe alloy and the lower part is made of Al-6.7Si-2Fe alloy. Microscopic examination and mechanical properties of the alloys used were conducted.

1. INTRODUCTION

Functionally graded materials are advanced composite materials utilized in engineering that exhibit a spatial variation in composition and/or structure to meet specific requirements. There is no text provided. FGMs can be classified into three categories based on their characteristics: chemical composition gradient FGMs, microstructural gradient FGMs, and porosity gradient FGMs [1]. Functionally graded materials (FGMs) are characterized by a gradual change in their chemical composition throughout the material. Microstructural gradient fiber-reinforced composites (FGMs) display a distinct and easily observable variation in their microstructure., as shown by studies [2-11]. These materials are used in a wide range of sectors including aerospace, nuclear, electrical, medicinal, military, and automotive. Aluminum alloys, in particular, are often used in the automobile industry as a result of more stringent environmental regulations [3,12-17].Cast aluminum alloy components, such as pistons, engine blocks, and rocker covers, are often found in ordinary automobiles. Aluminum alloys are regarded as sustainable materials since they can be recycled, are cost-effective, have a low weight, can be welded, and possess strong mechanical properties [4].

Aluminum-transition metal alloys have exceptional stability at relatively high temperatures, making them highly suitable for many automotive and aerospace applications that need lightweight alloys with high strength and a wide operating temperature range [5]. Cr is considered one of the most intriguing alloying elements for developing dispersion-hardened Al alloys that remain stable at high temperatures. This is because Cr has poor solubility and low diffusivity in solid Al.

Recent research has shown that gravity casting is a viable technique for producing aluminum-FGM pistons with two different compositions, resulting in improved mechanical strength and ductility [8]. Adding silicon to these alloys may affect their ability to withstand wear and prevent fatigue cracking [9,10]. Ensuring the strength of the link between alloys in Functionally Graded Materials (FGMs) is of utmost importance in the automotive industry. This necessitates comprehensive testing using micro-hardness tests, impact testing, and microstructural analysis. Researchers have investigated the use of vibration in the casting process to inject energy into the material, resulting in advantages such as refining the grain structure and reducing defects. Sequential stir casting with solidification under mechanical vibration is a technique used to produce functionally graded materials (FGMs) employing aluminum-silicon and aluminum-chromium alloys [11,12].

FGMs can be produced using many methods, such as gas-based, liquid-phase, and solid-phase techniques [2]. Centrifugal casting, squeeze casting, gravity casting, investment casting, and sintering are commonly used methods for producing metallic functionally graded materials (FGMs).

Multiple techniques for obtaining illegal access [4,5]. Gravity casting is a simple method used in the casting process to produce FGMs. This process employs a resilient mold, often constructed from steel. The mold is coated with a protective paint and then heated to a steady temperature, which enables the removal of the cast. The cast production sequence consists of many discrete steps: (i) cleansing the mold; (ii) executing the casting procedure; (iii) removing the cast; and (iv) severing the sprue.

As elucidated in reference [6], the casting process inevitably generates a specific degree of imperfections. These flaws, together with die design and microstructures, have an impact on the characteristics of castings.

Fiber-reinforced composite materials, commonly known as FGMs, are advanced materials used in engineering. These materials possess a complex structure with varying composition and/or form, which allows them to meet certain requirements and criteria. There are three main forms of FGMs: chemical composition gradient FGMs, microstructural gradient FGMs, and porosity gradient FGMs[1]. Functionally graded materials (FGMs) are characterized by a gradual variation in chemical composition across the material. Microstructural gradient fiber-reinforced composites, also referred to as FGMs, display a distinct and evident variation in their microstructure, as evidenced by references [2-11]. These materials are used in a wide range of sectors including aerospace, nuclear,electrical, medicinal, military, and automotive. Aluminum alloys are often used in the automobile industry, mostly because of more stringent environmental regulations [3,17].

Cast aluminum alloy components such as pistons, engine blocks, and rocker covers are often seen in daily automobiles. Aluminum alloys are regarded as sustainable materials since they can be recycled, are cost-effective, have a low weight, can be welded, and possess high mechanical strength [4].

Aluminum-transition metal alloys have exceptional stability at relatively high temperatures, making them very promising materials for many automotive and aerospace applications that need lightweight alloys with high strength and a wide operating temperature range [5]. Si is considered one of the most intriguing alloying elements for developing dispersion-hardened Al alloys that remain stable at high temperatures. These alloying elements have poor solubility and low diffusivity in solid Al.

Recent research has shown that gravity casting is a viable technique for producing aluminum-FGM pistons with two different compositions, resulting in improved mechanical strength and ductility [8]. The presence of silicon in these alloys might influence their resistance to wear and fatigue cracking [9,10]. Ensuring the strength of the link between alloys in Functionally Graded Materials (FGMs) is of utmost importance in the automotive industry. This necessitates comprehensive examination via micro-hardness tests, impact testing, and investigation of the material's microstructure using Scanning Electron Microscopy (SEM). Researchers have investigated the use of vibration in the casting process to inject energy into the material, resulting in advantages such as grain refinement and defect reduction. Sequential stir casting with solidification under mechanical vibration is a technique used to produce functionally graded materials (FGMs) employing aluminum-silicon and aluminum-chromium alloys [11,12]. When looking at the use of FGM in automotive applications, particularly with regards to aluminum alloys which are often used in this sector [8], it is indeed feasible to integrate the notion of FGM with aluminum alloys [9-12].

Because of their lightweight nature, especially in comparison to ferrous alloys, they play a crucial role in significantly reducing fuel consumption and the release of pollutants. In addition, they have exceptional resistance to certain forces and the ability to deform without breaking [13,14]. Functionally Graded Materials (FGMs) have several applications in the automobile industry, including engine pistons [9], leaf springs [15], and other uses. Casting and forging are the main techniques employed in the production of pistons [16–21].

In the work done by Park et al. (reference [22]), the forging method was modified to produce aluminum pistons by utilizing aluminum powder. A further study (reference [23]) concentrated on the production of high-performance pistons by additive manufacturing. Furthermore, as stated in reference [24], the EN AW 4032 alloy was utilized for the forging procedure of the pistons. A centrifugal casting process was used to make an aluminum piston with a microstructure-gradient functionally graded material (FGM). The superalloy was liquified and cast into a revolving mold. The mold design led to a substantial accumulation of primary silicon particles on the piston's head region.

This focused attention resulted in a simultaneous enhancement of both wear resistance and hardness. Similarly, Huang et al. [25] also utilize the same production technique. Engine pistons are commonly made from aluminum-silicon alloys because of their exceptional mechanical strength at elevated temperatures and desirable fatigue properties [16,25,26]. The EN AC 48000 is the most commonly utilized piston alloy. However, this alloy lacks sufficient malleability.

The piston skirt exhibits a minimal extension at the point of rupture, potentially leading to fatigue failure. In order to avoid this issue, it is advisable to utilize a more pliable alloy for the skirt and a resilient alloy for the piston crown in the FGM. This study outlines the process of creating a chemical-composition-gradient FGM (Functionally Graded Material) specifically designed for a car piston. The FGM was produced using successive gravity casting, with the piston in contact with a distinct alloy composition. This Finite Element Analysis (FEA) model was specifically designed to focus on the process parameters and their influence on the resulting mechanical properties.

2. MATERIALS AND METHODS

2.1 Al-Si-Fe alloys sample preparation

Pieces of pistons were was melted in the ceramic crucible and maintained at 800° C. iron powders in progressive quantities were added gradually to the melt . The powders were deviled into parts, each at which was enveloped by aluminum foil hated to 300° C before adding to the melt. Table 1. showed Chemical composition of Al-Si-Fe alloys [3].

Table 1. Chemical composition of Al-Si-Fe alloys.

Sample	Si wt.%	Fe wt.%	Cu wt.%	Cr wt.%	Al wt.%
A1	17	2	0.87	0. 86	Bal.
A2	6.7	2	0.8	0.244	Bal.

2.2. Fabrication of the FGM alloy samples

The FG alloy samples were fabricated based on the prepared alloy samples. Tow casting procedure were employed to fabricate tow gropes of cast. The first was cast under the effect of mechanical vibration the second was cast without such effect.

The FG alloys were produced using a process of sequential gravity casting, where the first composition was casted first, followed by the second composition. The time interval between the two casting processes and the pouring temperature were set to 20 seconds and 900 degrees Celsius, respectively.

Theirs varieties of FG castings were manufactured. The types are Al-6.7at.%Si-2at.%Fe and Al-17at.%Si-2at.%Fe.

During the casting process, the temperature of the alloy was elevated beyond its liquid state. The molten substance was introduced into a steel mold that had been preheated and had a cylindrical chamber of 24 mm in diameter and 150 mm in height. The temperature of the mold was raised to 400 degrees Celsius. In order to achieve casting under the influence of vibrations, mechanical vibrations are initiated prior to pouring and are maintained until the solidification process is fully completed.

3. EXPERIMENTAL WORK

3.1. X-ray Diffraction (XRD)

Specimens with (20 x 10 mm) at interface zone were prepared for X-ray diffraction analysis. The measure conditions are Target: Cu, wave length of 1.54060 , voltage and current are 30 KV and 15 mA respectively, Scanning step of 0.05 with a step time of 2 s, and a scanning range of (5°-80°) were used [17].

3.2. Microstructure analyses

The test conducted on the produced FGM sample Specimens measuring 130 mm in length were used. The specimen was flattened by employing SiC grinding sheets with varying roughness levels (400, 800, 1000, 1200, 2000, grit size). The grinding and polishing procedures were carried out utilizing the MP-2B grinder polisher machine.

The Al-Si-Fe alloy specimens were subjected to etching using a solution (2ml HF, 3ml HNO3, 5ml HCl$^+$ Distilled 190ml water) for a duration of 15 seconds. Similarly, the Al-Si-Fe alloy specimens underwent etching using the same solution and duration at room temperature [19]. Subsequently, the specimens were rinsed with distilled water and dried using an electric drier. A specimen's microstructure was examined using an optical microscope at a magnification of 400X. Experiments were performed at ambient temperature with a compression rate of 0.5 millimeters per minute.

3.4. Vickers Hardness Test

The Vickers hardness test was carried out according to ASTM(E10-15a), with a load of 10 Kg. Appropriate grinding and polishing were carried out before subjecting the specimens to the test. The test was performed at every 5 mm along the specimens length of 130 mm, At the interface region the test were carried out at every 0.25 mm. The test was carried out via a hardness tester type (HVS-1000).

3.5. Tensile Test

Standard specimens were prepared with dimensions according to ASTM E8 standard [1]. Computer control universal testing machine model (WDW) was used with tensile speed rate of (0.2 mm/min) at room temperature. Experiments were performed at standard room temperature

3.6. Compression test

Compression test specimens were fabricated from the cast alloy samples. The specimens possessed a configuration and dimensions of 23 mm in diameter and 46 mm in height, with the interface positioned in the center as per the ASTM (E8M-04) standard. The compression tests were performed at ambient temperature at a speed of 0.5 mm/min.

4. RUSULTS AND DISCUSSION

4.1. (XRD) analyses

The charts of the XRD for sample in zone of that functionally graded material was fabricated by casting two deferent alloy, Peaks match with the standard chart of the X-ray diffraction for each phase Figure 1. represents XRD for FG sample with vibration, there is no deferent between alloy with and without vibration in components, the result including α-Al phase, Si, Al2Cu, Al5FeSi.

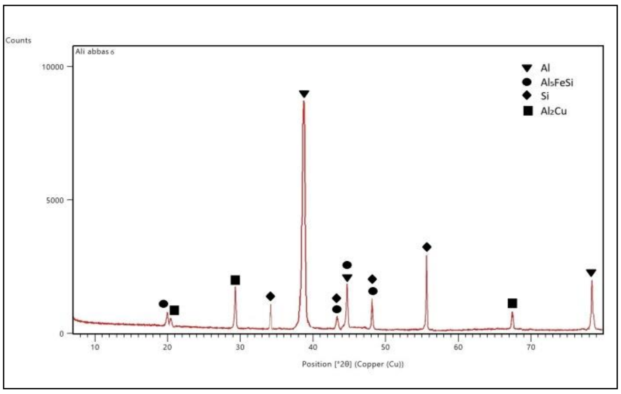

Fig. 1. Maximum hardness value

4.2. Microstructure

Figure 2. shows the microstructures of the samples. During hardening, in the intervise zone, there are differences that can be identified by the microstructure on both sides of the zone. This is due to the difference in alloy chemical composition. Also, the absence of pores that appear in samples In each sample, there is no lost contact or dissolution between the two surfaces of the alloy.

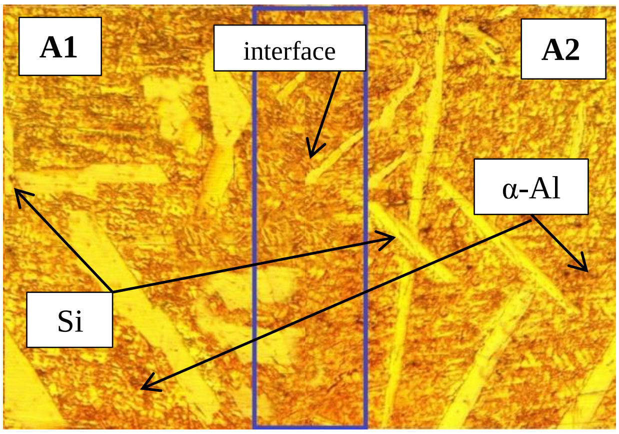

Fig. 2. Microstructures of FG at inteface zone

4.3. Vickers Hardness Test

Figure 3 displays the results of the Vickers hardness test conducted on the alloy samples. The A2 alloy has a higher level of hardness. When comparing with sample A1 in the Al-Si-Fe alloy. The increase in these values can be attributable to the comparatively high hardness of the silicon particles.

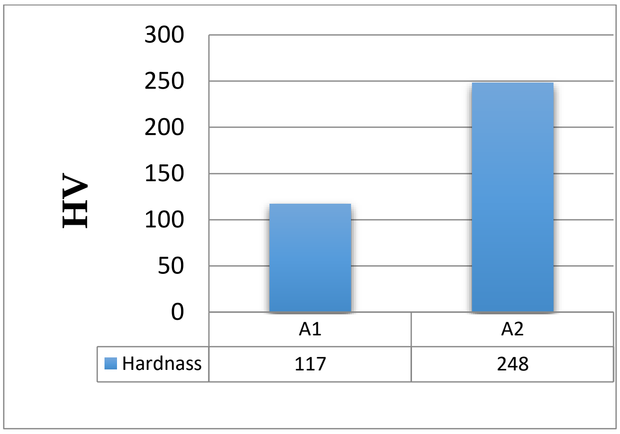

Fig. 3. Maximum hardness value.

The figure 4. shows the Vickers hardness along samples length. There is a change in the hardness value for both bars at the joint area at interface area due to the difference in the chemical composition of the alloy.

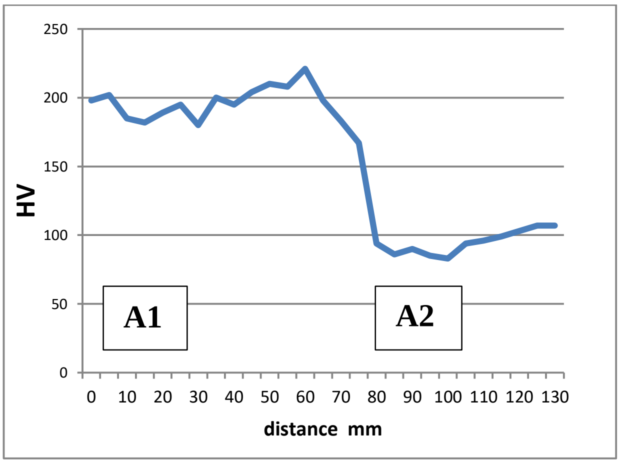

Fig. 4. Vickers hardness along the length of the samples.

The hardness values on both sides of the interface, at a spacing of 5 microns, are depicted in Figure 5. It has been noted that the hardness value rises as the distance changes, which is attributed to the interaction of the chemical composition of the alloy.

Fig. 5. Hardness values at interface.

4.4. Tensile Test

Tensile test results for the samples under the with an elongation percentage of 0.0.8%, The reason is due to the strengthening of the matrix α-Al by means of compounds that are uniformly distributed within the alloy.

4.5. Compression test rustles

The results of compression of samples are shown showed values of 431 MPs. This is due to the This is due to the presence of compounds and the presence of free silicon, which acts as an obstacle to the movement of dislocations, which leads to strengthening the matrix.

5. CONCLUSION

This study involved the production of innovative forms of FGM through the manipulation of successional casting techniques. The alloy consisting of 6.7% percent Si and 2% percent iron, together with the alloy consisting of 17% percent Si and 2% percent iron, was used to produce castings that exhibited high quality and minimal retained flaws. The presence of Fe was considered in order to enhance the mechanical characteristics of the as-cast FGM, particularly by the nucleation including α-Al phase, Si, Al2Cu, Al5FeSi. Functionally graded materials were castings that were made and then subjected to mechanical testing. The sequential casting method is an effective method for producing materials with graded properties with similar bases.

- The difference in microscopic structure is due to the difference in the concentration of silicon, which forms compounds with the presence of slicon and iron.
- The XRD test showed the presence of compounds that would enhance the matrix.
- There is no defect in the interface area that could have caused the part to fail.
- Sequential casting is an efficient method for manufacturing FG with different chemical compositions.

REFERENCES

[1] C. Botero, A. Koptyug, W. Sjöström, E. Jiménez-Piqué, A. Şelte, and L. E. Rännar, "Functionally graded steels obtained via electron beam powder bed fusion," *Key Engineering Materials*, vol. 964, pp. 79–84, 2023. [Online]. Available: doi: 10.4028/p-xaC6qO.

[2] K. Młynarek-Żak, W. Pakieła, D. Łukowiec, A. Bajorek, P. Gębara, A. Szakál, and R. Babilas, "Structure and selected properties of Al–Cr–Fe alloys with the presence of structurally complex alloy phases," *Scientific Reports*, vol. 12, p. 14194, 2022. [Online]. Available: doi: 10.1038/s41598-022-17870-0.

[3] R. Li, W. Yu, Y. Zhang, C. Li, Y. Qu, S. Nie, and B. Yu, "Effect of phase proportion on wear behavior of Al–Cr–Fe–Ni dual-phase high entropy alloys," *Metallography, Microstructure, and Analysis*, vol. 10, pp. 106–115, 2021. [Online]. Available: doi: 10.1007/s13632-020-00709-3.

[4] S. Yang, J. Lu, F. Xing, L. Zhang, and Y. Zhong, "Revisit the VEC rule in high entropy alloys (HEAs) with high-throughput CALPHAD approach and its applications for material design—A case study with Al–Co–Cr–Fe–Ni system," *Acta Materialia*, vol. 192, pp. 11–19, 2020. [Online]. Available: doi: 10.1016/j.actamat.2020.03.039.

[5] T. M. Ribeiro, E. Catellan, A. Garcia, and C. A. dos Santos, "The effects of Cr addition on microstructure, hardness and tensile properties of as-cast Al–3.8 wt.% Cu–(Cr) alloys," *Journal of Materials Research and Technology*, vol. 9, no. 3, pp. 6620–6631, 2020. [Online]. Available: doi: 10.1016/j.jmrt.2020.04.054.

[6] C. M. Koller, A. Kirnbauer, R. Hahn, B. Widrig, S. Kolozsvári, J. Ramm, and P. H. Mayrhofer, "Oxidation behavior of intermetallic Al-Cr and Al-Cr-Fe macroparticles," *Journal of Vacuum Science & Technology A*, vol. 35, no. 6, 2017. [Online]. Available: doi: 10.2139/ssrn.4705444.

[7] A. P. de Araujo, L. Micheloti, C. S. Kiminami, and P. Gargarella, "Microstructure, phase formation and properties of rapid solidified Al–Fe–Cr–Ti alloys," *Materials Science and Technology*, vol. 36, no. 11, pp. 1205–1214, 2020. [Online]. Available: doi: 10.1080/02670836.2020.1763555.

[8] Švecová, E. Tillová, L. Kuchariková, and V. Knap, "Possibilities of predicting undesirable iron intermetallic phases in secondary Al-alloys," *Transportation Research Procedia*, vol. 55, pp. 797–804, 2021. [Online]. Available: doi: 10.3390/electronicmat3010001.

[9] E. Fracchia, S. Lombardo, and M. Rosso, "Case study of a functionally graded aluminum part," *Applied Sciences*, vol. 8, no. 7, p. 1113, 2018. [Online]. Available: doi: 10.3390/app8071113.

[10] E. Fracchia, F. S. Gobber, M. Rosso, M. Actis Grande, J. Bidulská, and R. Bidulský, "Junction characterization in a functionally graded aluminum part," *Materials*, vol. 12, no. 21, p. 3475, 2019. [Online]. Available: doi: 10.3390/ma12213475.

[11] T. Gao, Z. Li, Y. Zhang, J. Qin, and X. Liu, "Phase evolution of β-Al5FeSi during recycling of Al–Si–Fe alloys by Mg melt," *International Journal of Metalcasting*, vol. 13, pp. 473–478, 2019. [Online]. Available: doi: 10.1007/s40962-018-0279-3.

[12] Wang, S. Liu, X. Bai, X. Zhou, and X. Han, "Oxidation behavior of Fe–Al–Cr alloy at high temperature: Experiment and a first principle study," *Vacuum*, vol. 173, p. 109144, 2020. [Online]. Available: doi: 10.1016/j.vacuum.2019.109144.

[13] H. Shi, A. Jianu, R. Fetzer, D. V. Szabo, S. Schlabach, A. Weisenburger, and G. Mueller, "Compatibility and microstructure evolution of Al-Cr-Fe-Ni high entropy model alloys exposed to oxygen-containing molten lead," *Corrosion Science*, vol. 189, p. 109593, 2021. [Online]. Available: doi: 10.1016/j.corsci.2021.109593.

[14] Z. Que, Y. Wang, C. L. Mendis, C. Fang, J. Xia, X. Zhou, and Z. Fan, "Understanding Fe-containing intermetallic compounds in Al alloys: an overview of recent advances from the LiME research hub," *Metals*, vol. 12, no. 10, p. 1677, 2022. [Online]. Available: doi: 10.3390/met12101677.

[15] T. Gao, Z. Li, Y. Zhang, J. Qin, and X. Liu, "Phase evolution of β-Al5FeSi during recycling of Al–Si–Fe alloys by Mg melt," *International Journal of Metalcasting*, vol. 13, pp. 473–478, 2019. [Online]. Available: doi: 10.1007/s40962-018-0279-3.

[16] O. Y. Sheshukov and V. V. Kataev, "Influence of Titanium and Zirconium on the Structure and Heat-Resistance of Low-Carbon Iron–Aluminum Alloys," *Steel in Translation*, vol. 51, pp. 621–626, 2021. [Online]. Available: doi: 10.1179/174328407X168766.

[17] H. Z. Chen, B. R. Li, B. Wen, Q. Ye, and N. Q. Zhang, "Corrosion behaviours of iron-chromium-aluminium steel near the melting point of various eutectic salts," *Solar Energy Materials and Solar Cells*, vol. 210, p. 110510, 2020. [Online]. Available: doi: 10.1016/j.solmat.2020.110510.

[18] B. A. Behrens, K. Brunotte, T. Petersen, and R. Relge, "Investigation on the microstructure of ECAP-processed iron-aluminium alloys," *Materials*, vol. 14, no. 1, p. 219, 2021. [Online]. Available: doi: 10.3390/ma14010219.

[19] D. Siekaniec, D. Kopyciński, E. Tyrała, E. Guzik, and A. Szczęsny, "Optimisation of solidification structure and properties of hypoeutectic chromium cast iron," *Materials*, vol. 15, no. 18, p. 6243, 2022. [Online]. Available: doi: 10.3390/ma15186243.

[20] R. Babilas, A. Bajorek, M. Spilka, A. Radoń, and W. Łoński, "Structure and corrosion resistance of Al–Cu–Fe alloys," *Progress in Natural Science: Materials International*, vol. 30, no. 3, pp. 393–401, 2020. [Online]. Available: doi: 10.1016/j.pnsc.2020.06.002.

[21] M. T. Pérez-Prado, A. Martin, D. F. Shi, S. Milenkovic, and C. M. Cepeda-Jiménez, "An Al-5Fe-6Cr alloy with outstanding high temperature mechanical behavior by laser powder bed fusion," *Additive Manufacturing*, vol. 55, p. 102828, 2022. [Online]. Available: doi: 10.1016/j.addma.2022.102828.

[22] C. M. Koller, A. Kirnbauer, V. Dalbauer, S. Kolozsvári, J. Ramm, and P. H. Mayrhofer, "On the oxidation behavior of cathodic arc evaporated Al-Cr-Fe and Al-Cr-Fe-O coatings. I," *Journal of Vacuum Science & Technology A*, vol. 37, no. 4, 2019. [Online]. Available: doi: 10.1116/1.5099123.

[23] F. Sourani, M. H. Enayati, and A. H. W. Ngan, "On the in situ synthesis of (Fe, Cr) Al and (Fe, Cr) Al–Al2O3 nanostructured materials," *Materials Research Express*, vol. 6, no. 8, p. 0850c9, 2019. [Online]. Available: doi: 10.1088/2053-1591/ab24f5.

[24] V. S. Skorodzievskii, A. I. Ustinov, S. S. Polishchuk, S. A. Demchenkov, and V. O. Telychko, "Dissipative properties of Al-(Fe, Cr) vacuum coatings with different composite structures," *Surface and Coatings Technology*,

vol. 367, pp. 179–186, 2019. [Online]. Available: doi: 10.1016/j.surfcoat.2019.03.074.

[25] B. A. I. G. Muneer, H. R. Ammar, A. H. Seikh, J. A. Mohammed, F. A. M. Fahad, and A. Alaboodi, "Thermal stability of nanocrystalline Al−10Fe−5Cr bulk alloy," *Transactions of Nonferrous Metals Society of China*, vol. 29, no. 2, pp. 242–252, 2019. [Online]. Available: doi: 10.1016/S1003-6326(16)64128-6.

[26] R. Shockner, I. Edry, M. Pinkas, and L. Meshi, "Systematic study of the effect of Cr on the microstructure, phase content and hardness of the AlCrxFeCoNi alloys," *Journal of Alloys and Compounds*, vol. 940, p. 168897, 2023. [Online]. Available: doi: 10.1016/j.jallcom.2023.168897.