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Optimization of the Aluminum Alloy Phase Composition Based on Si-0.6% Mn-0.5% with Changing the Iron Content

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Abstract. The article investigates the effect of iron content on the phase composition, microstructure, mechanical properties and electrical conductivity of the Si-0.6% Mn-0.5% aluminum alloy. Experimental alloys with iron content ranging from 0.1% to 2.0% were studied using X-ray diffraction analysis (XRD), optical and scanning electron microscopy, hardness and tensile strength testing, as well as eddy-current conductivity measurements. It was established that an iron content of 0.8% provides the most optimal balance of properties: hardness - 60 HB, tensile strength - 170 MPa, ductility - 16%, and electrical resistivity - 33 μΩ·m. With further increase of iron concentration, hardness and strength increase but electrical conductivity decreases significantly due to the formation of AlFeSi and Al_3Fe phases. The obtained results demonstrate that controlling the iron content allows optimization of aluminum alloys for application in electrical engineering, construction and automotive industries, where both high mechanical strength and stable conductivity are required.

Keywords: aluminum alloy, iron, phase composition, hardness, electrical conductivity, phase diagram, microstructure, heat treatment.

Introduction

Aluminum alloys are among the most demanded structural materials due to their low density, high corrosion resistance, and technological flexibility. They are widely applied in the aerospace, automotive, construction, and electrical industries [1]. However, achieving a balance between mechanical properties and electrical conductivity remains a challenging task for alloy developers.

One of the key factors influencing the performance of aluminum alloys is the presence of iron impurities. Iron is an unavoidable element in most aluminum alloys, and depending on its content it can either improve strength or significantly deteriorate ductility and conductivity [2]. Previous studies have shown that excessive iron leads to the formation of intermetallic compounds such as Al_3Fe and AlFeSi, which cause embrittlement and reduce the electrical conductivity of alloys. At the same time, controlled addition of iron in limited amounts may improve hardness and tensile strength.

Despite the large body of research, most works have focused on Al-Si, Al-Mn or Al-Zr alloys separately, whereas systematic studies of the Si-0.6% Mn-0.5% system with varying Fe content are limited. The scientific gap lies in the absence of quantitative data on how gradual changes in iron concentration affect the phase composition, microstructure, mechanical strength and electrical conductivity in this particular system.

The purpose of this research is to determine the optimal iron content in the Si-0.6% Mn-0.5% aluminum alloy that ensures the best combination of strength, ductility, and electrical conductivity [3]. It is expected that the experimental results will identify a specific Fe concentration that balances these properties, thus contributing to the development of new high-performance aluminum alloys for engineering and electrical applications.

Materials and methods

Samples of Si-0.6% Mn-0.5% alloy with different Fe contents were prepared for testing. The samples were obtained by casting into a metal mold followed by heat treatment at 550 °C within 4 hours.

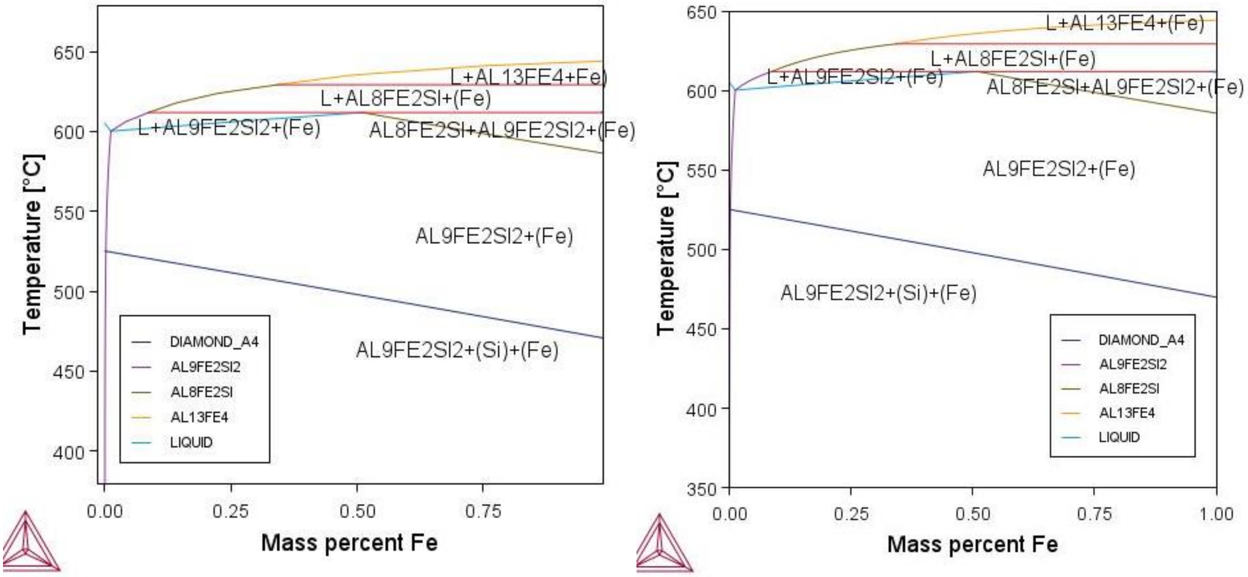
Aluminum alloys with different iron contents in the range from 0.1% to 2% were used for testing. The alloys were prepared by melting and chill casting, and then subjected to the thermal analysis.

The chemical composition was determined using a Vanta Element-S metal analyzer (Table 1).

Table 1. Chemical composition of experimental aluminum alloys of the Al-Si-Mn-Fe system (wt. %)

No.	Name	Si	Mn	Fe	Al (the rest)
1	Alloy 1	0.6	0.5	0.1	The rest
2	Alloy 2	0.6	0.5	0.3	The rest
3	Alloy 3	0.6	0.5	0.5	The rest
4	Alloy 4	0.6	0.5	0.8	The rest
5	Alloy 5	0.6	0.5	1	The rest
6	Alloy 6	0.6	0.5	1.5	The rest
7	Alloy 7	0.6	0.5	2	The rest

The X-ray diffraction analysis (XRD) was used to identify the phases and their volume fractions. The X-ray phase analysis was performed on an EMPYREAN diffractometer with CuKα radiation, which ensured high accuracy of phase identification. X-ray diffraction showed that with increasing the iron content, in the alloy new phases were formed. With the iron content of up to 0.8%, α-Al and Si remain the main phases; and the AlFeSi phase also appears. With increasing the iron content to 2%, the phase components AlFeSi and Al_3Fe begin to predominate, which leads to significant changes in the microstructure [4]. The TTAL8 database of the ThermoCalc software package was used for the study. It includes the information of the phases formed in aluminum alloys. Figure 1 shows the polythermal sections of the Al-Fe-Si alloy at 450 °C and 600 °C.

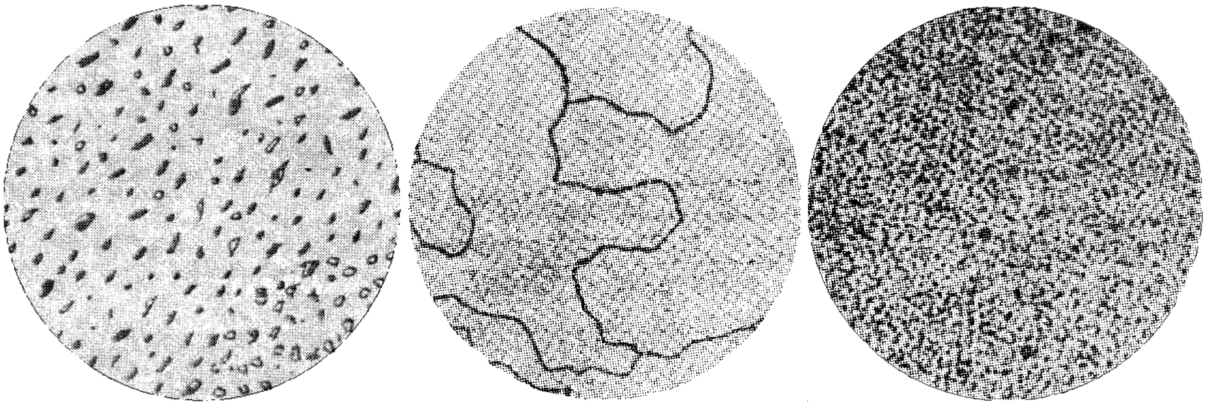


a) b)

Fig.1. - Polythermal sections of the phase diagram of the Al-Fe-Si system at 450 °C (a) and 600 °C (b)

The microstructure was studied using optical (Magus Metal VD700 BD LCD) and scanning electron microscopy (TESCAN VEGA 3) [5-6].

According to the literature data, metallographic studies using a scanning electron microscope showed that with increasing the iron content in the alloy, aggregation of the AlFeSi and Al_3Fe phases occurs, which leads to a coarser structure with increasing the grain size. Alloys with the iron content of 0.8% have the most optimal microstructure with the uniform distribution of phases and smaller grain sizes (Figure 2).



a b c

a) after annealing; b) after quenching from 530°C; c) after quenching and artificial aging at 250°C

Fig.2. - Microstructure of the aluminum alloy of the Al-Fe-Si system under different heat treatment conditions (x250) [7]

Figure 3 shows the microstructure of Al-Si-Mn-Fe alloys with variable iron contents obtained using a scanning microscope. Micrograph 3a shows the formation of primary aluminum grains (designated as (Al)) and precipitation of the intermetallic phase Al_6Fe. These phases are formed along the grain boundaries of aluminum. Micrograph 3b shows a further change in the microstructure. In addition to aluminum grains (Al), there are precipitates of the intermetallic phase Al_3Fe [8-10]. Their size and distribution indicate increasing the iron content of the alloy, which contributes to changing the phase composition. Micrograph 3c shows that with increasing the iron content in the alloy, intermetallic compounds of a more complex composition are formed, such as Al_3Fe_2Si. The phase is distributed along the grain boundaries, which indicates a significant effect of iron on the microstructure of the alloy. Micrograph 3g shows the microstructure characterized by the formation of large intermetallic phases of Al_3Fe_2.

These changes in the microstructure demonstrate how the iron content of aluminum alloys affects the phase composition. Increasing the iron concentration promotes the formation of more complex intermetallic compounds, which in turn affects the mechanical properties and electrical conductivity of the alloy.

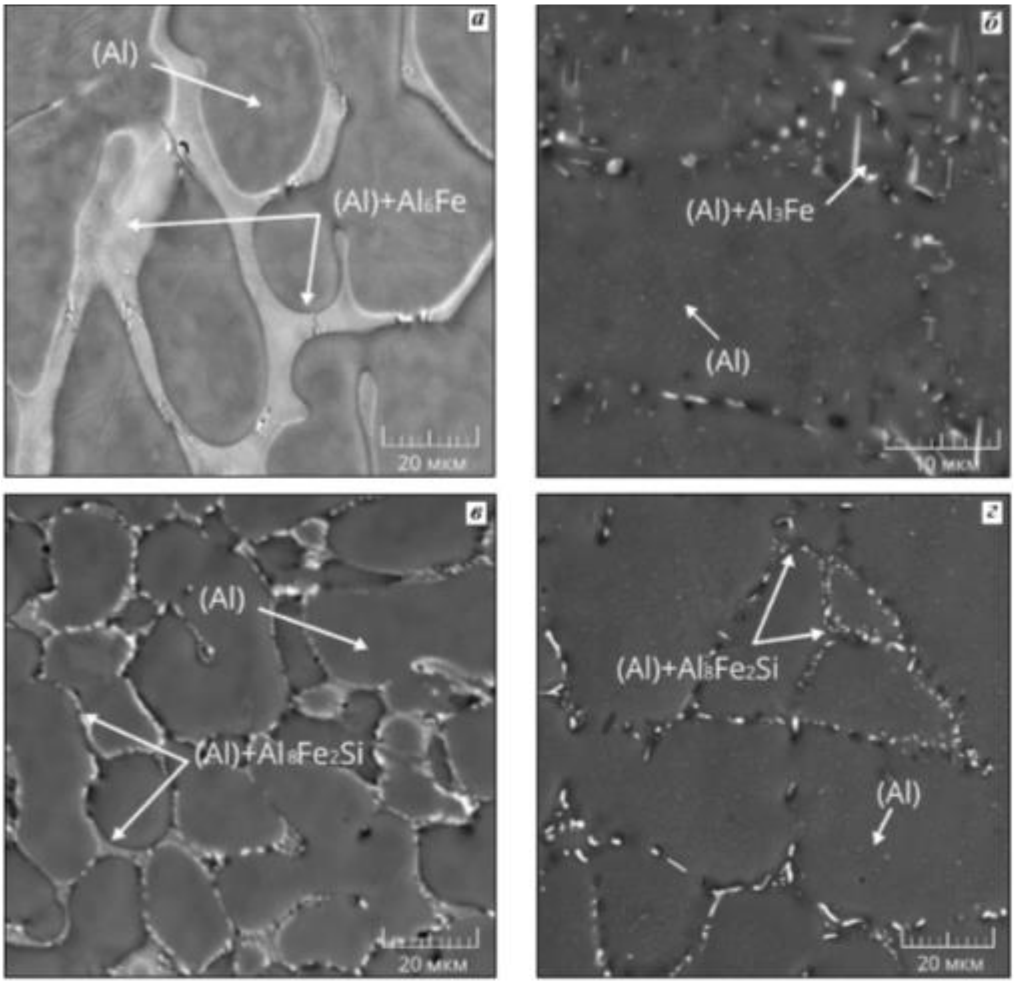


Fig.3. - Detailed microstructure of Al-Si-Mn-Fe alloys with variable iron contents

Vickers hardness was determined using a Willson 1150 hardness tester with the following parameters: the load 50 N, the holding time 15 s.

To determine tensile strength, an Instron universal testing machine with the 100 kN load frame was used. The tests were carried out using standard cylindrical samples in accordance with the ASTM E8/E8M standard [11-13]. The setup was equipped with highly sensitive sensors that ensured the measurement accuracy and reproducibility of results.

The measured values of hardness and strength show that increasing the iron content leads to increasing the alloy hardness but reduces its ductility. The most optimal mechanical properties are observed in the alloys with the iron content of 0.8%, which is caused by the balance between strength and ductility.

Table 2. The iron content effect on the mechanical properties of aluminum alloys of the Al-Si-Mn system

No.	Fe content, %	Hardness, HB	Tensile strength, MPa	Plasticity, %
1	0,1	45	120	20
2	0,3	55	140	19
3	0,5	58	160	18
4	0,8	60	170	16
5	1,0	70	180	15
6	1,5	80	210	12
7	2,0	90	220	10

For each alloy, specific electrical conductivity was measured using the eddy current method on a VE-26NP device, and then converted into specific electrical resistance [14-16].

Electrical conductivity measurements (Table 3) showed that with increasing the iron content, electrical conductivity of the alloy decreased significantly. This was due to the formation of the AlFeSi and Al_3Fe phases that affected the movement of electrons and reduced the overall conductivity of the material. For alloys with the iron content of 0.8%, the minimal decrease in electrical conductivity was observed, which made them optimal for use where good conductivity was important.

Table 3. Changing electrical conductivity of aluminum alloys of the Al–Si–Mn system depending on the iron content

No.	Fe content, %	Electrical conductivity (μΩ·m)	Basic phases
1	0.1	38	α-Al, Si
2	0.3	37	α-Al, Si
3	0.5	35	α-Al, Si, AlFeSi
4	0.8	33	α-Al, Si, AlFeSi
5	1.0	30	α-Al, Si, AlFeSi, Al_3Fe
6	1.5	25	α-Al, Si, AlFeSi, Al_3Fe
7	2.0	20	α-Al, Si, Al_3Fe

Discussion

Optimization of the phase composition of aluminum alloy Si–0.6% Mn–0.5% by changing the iron content reveales patterns that can be used to improve the mechanical properties and electrical conductivity of materials. The greatest improvement in strength characteristics and the minimum decrease in electrical conductivity are observed at the iron content of 0.8%, which makes this composition optimal for various technical applications requiring good mechanical properties and electrical conductivity comparison.

The diagram provided shows the key indicators for various alloys. For alloy 3 (0.8% Fe), the following important aspects can be noted (Figure 4).

The electrical conductivity value is slightly lower than that of alloys with a lower iron content but high enough to remain acceptable for engineering applications. Alloy 3 has the optimal hardness (about 60 HB), which provides sufficient strength for most engineering tasks. Strength reaches the maximum level (about 170 MPa), while maintaining a balance between strength and ductility. Although ductility is slightly lower than that of alloys with a lower Fe content, it remains acceptable (about 16%), which makes the alloy suitable for structural materials.

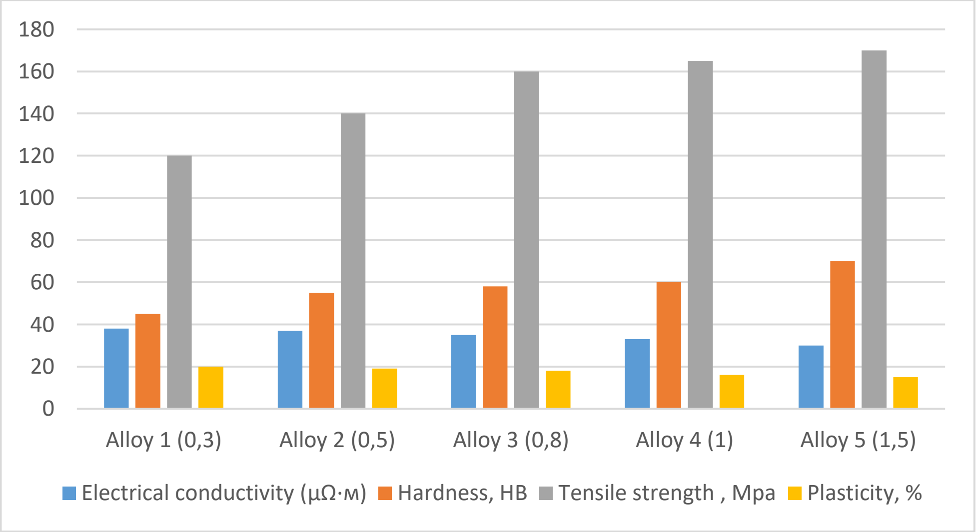


Fig.4. - Results of studying the iron content effect on the properties of aluminum alloys

Alloy 3 (0.8% Fe) exhibits the most optimal combination of properties, including high strength, good hardness and sufficient electrical conductivity. This makes it an ideal choice for industrial applications where it is important to ensure a balance between mechanical properties and electrical conductivity.

Conclusion

Changing the iron content in Si–0.6% Mn–0.5% aluminum alloys has a significant effect on their phase composition, microstructure, mechanical properties and electrical conductivity. The optimal iron content is recognized to be 0.8%, which provides a combination of high strength, ductility and electrical conductivity. This makes this alloy promising for a wide range of engineering tasks.

This alloy is especially suitable for use in structures that require high strength and stable conductivity, such as in the aviation, automotive and construction industries, as well as for electrical components. In addition, the study shows that the iron content of 0.8% contributes to increased corrosion resistance, which expands the scope of its application in aggressive environments.

Optimization of the phase composition and microstructure of this alloy opens up opportunities for further studies aimed at improving performance characteristics. Adjusting the iron content is the key tool for developing materials with specified properties that meet present day industrial requirements.

Thus, the developed aluminum alloy with the optimal iron content of 0.8% can become the basis for developing new materials with improved characteristics. This opens up prospects for its application in the production of electronics, energy equipment and high-tech structures.

References

[1] Ivanov A.A., Petrov B.B. The influence of iron on the properties of aluminum alloys // Metallovedenie. 2020. Vol. 45, P. 123-130.

[2] Johnson M., Smith R. High-temperature properties of Al-Zr alloys // Journal of Materials Science, 2019, Vol. 54., P. 4567–4576.

[3] Smirnov A.A., Ivanov V.V. The influence of manganese on the properties of aluminum alloys // Metallovedenie, 2021, Vol. 46, P. 134-140.

[4] Brown T., Smith J. Influence of Fe on Al-Mn alloys // Journal of Materials Science, 2020, Vol. 55, P. 5678–5685.

[5] Deng Y., Yin Zh., Pan Q., Xu G., Duan Yu., Wang Y. Na-no-structure evolution of secondary Al3(Sc1–xZrx) particles during superplastic deformation and their effects on deformation mechanism in Al—Zn—Mg alloys //J. Alloys and Compnd, 2017, No. 695, P. 142—153.

[6] Gao T., Ceguerra A., Breen A., Liu X., Wu Y., Ringer S. Precipitation behaviors of cubic and tetragonal Zr-rich phase in Al—(Si—) Zr alloys //J. Alloys and Compounds, 2016, No. 674, P. 125—130.

[7] Anisovich A. G. Microstructures of ferrous and non–ferrous metals. – Minsk: Belorusskaya nauka, 2015. – 131 p. - ISBN 978-985-08-1883-6.

[5] Toleuova, A.R., Dostayeva, A.M., Zharkevich, O.M., Adilkanovva, M.A. Calculating and experimental studying phase transformations in the al-zr-fe-si system alloys //Metalurgija, 2020, 59(4), страницы 543–546.

[6] Kulikov, V.Y., Aubakirov, D.R., Kvon, S.S., Dostaeva, A.M., Shcherbakova, E.P. Use of Wear-Resistant Materials in the Kazakhstani Metallurgical Industry Metallurgist, 2019, 62(9-10), страницы 1068–1072.

[7] Batessova F., Omirbay R., Sattarova G., Zholmagambetov N., Zholmagambetov S., Dostayeva A., Suleimenov, N., Medeubayev, N. Reducing industrial noise by the use of damping alloys when manufacturing mining equipment parts //Heliyon, 2023, 9(6), e17152.

[8] Aubakirov D.R., Issagulov A.Z., Akberdin A.A., Kvon Sv.S., Kulikov V.Yu., Arinova S.K., Dostaeva A.M., Chsherbakova Ye.P., Sarkenov B.B., Narembekova A.K. Influence of boron- and barium-containing modifiers on the structure of low-chromium cast iron // Heliyon, 2022, 8(11), e11496.

[9] Dostayeva A.M., Erahtina I.I., N.R. Zholmagambetov N.R., Medeubayev N.A., Zholmagambetov S.R. Investigation of aluminum-titanium alloys production and labor safety in metal smelting process // Metalurgija, 2021, 60(3-4), P. 403–406,

[11] Kovalyova T., Eremin E., Arinova S., Medvedeva I., Dostayeva A. Enhancing surface roughness of castings when sand-resin mold casting //Metalurgija, 2017, 56(1-2).

[12] Belov N. A., Dostaeva A.M., Shurkin P. K., Korotkova N. O., Yakovlev A. A. The effect of annealing on the electrical resistance and hardness of hot-rolled aluminum alloy sheets containing up to 0.5% Zr //Izvestiya vuzov non-ferrous Metallurgy, 2016, No. 3, P.48-55.

[13] Kowalski P., Nowak M., Zielinska A. Effect of Fe content on the mechanical properties and electrical conductivity of Al–Si alloys // Archives of Metallurgy and Materials, 2020, Vol. 65, No. 3, P. 987–994.

[14] Kim S., Lee J., Park H. Effect of iron content on the structure and properties of Al–Si–Mn alloys subjected to severe plastic deformation //Materials Science and Engineering A, 2024, Vol. 891, P. 145–157.

[15] Suleyev B., Issagulov A., Dostayeva A., Aubakirov D., Sultanbek T. Silicon and Manganese Effect on the Phase Composition of an Al-Fe Alloy and the Use of the ThermoCalc Software Complex for Thermodynamic Analysis //Alloys, 2025, 4, 10. https://doi.org/10.3390/alloys4020010

[16] Brown T., Chen Y., Gupta A. Aluminum alloys for electrical engineering: a review // Journal of Materials Science, 2024, Vol. 59, P. 11234–11250.

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