CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY
ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

Check for updates

UDC 669.017

Original article

https://doi.org/10.23947/2541-9129-2023-7-3-66-76

Influence of the Structural-Phase Composition of the Initial Charge Material on the Qualitative Characteristics of Castings from Al-Si-Mg System Alloy

Vladimir S. Muratov, **Mikhail S. Kazakov** ✉
Samara State Technical University, Samara, Russian Federation
✉Kazakov.mishel@gmail.com

Introduction. The work focuses on solving quality problems of castings made of Al-Si-Mg alloy (AK9). The paper draws attention to the absence of a unified theory of alloy modification and the need to find solutions that ensure good product quality. The reasons for bad quality due to the weak justification of the choice of the manufacturer of the initial charge material — ingots are considered. Ingots from two suppliers are compared in terms of the structural-phase state. The paper shows how it causes defects in castings. The inefficiency of traditional methods of suppressing the formation of brittle plates of the iron-containing phase in the alloy of the Al-Si-Mg system due to the presence of Mn in the chemical composition of the alloy is noted. If the specified flaw is inherited from the source material, the generally accepted approach does not work. The article formulates the recommendations for solving this problem. The introduction of the proposed approach into production practice can open the way to solving an important applied task — to improve the wording of tasks for tenders. The relevance of the study is due to the widespread use of alloys of the Al-Si-Mg (AK9) system in modern mechanical engineering, including in aerospace structures. The work objective is to study the influence of the structural-phase state of the source material on the qualitative characteristics of finished castings from the Al-Si-Mg alloy system.

Materials and Methods. Eight casts were analyzed, in which ingots from two manufacturers were used. Radiography revealed a correlation between the fracture structure of castings, structure and quality indicators. Scanning electron microscopy was used to analyze the microstructure and chemical composition of the phases. When setting quality requirements, the authors proceeded from the existing industry and state standards. The conditions of heat treatment of samples were taken from the same documents. The spectrograms were visualized as graphs showing the intensity of the element peak in the Auger spectrum and the energy of the electrons resulting from the Auger effect.

Results. The results of radiography gave grounds to assert that the products provided by supplier No. 1 had significant advantages in terms of quality. If we focused on the industry standard, the exclusion of the 2nd supplier's ingots from the process ensured the production of products without casting defects at the level of 73 %. Otherwise, this figure did not exceed 57 %. The rejection indicators were discontinuities, clusters of flaws, high porosity. After melting 5–8, which involved the materials of the 2nd manufacturer, the fractures of the samples after rupture were investigated. Locations with smooth, viscous and mixed relief are highlighted. An increase of up to ×500 made it possible to establish insignificant areas with a viscous relief, which was characteristic of brittle fracture by the cleavage mechanism. The absence of inclusions and liquations was established. The microstructure of the sections from discontinuous samples was considered. It turned out that it corresponded to the modified and heat-treated state of the AK9ch alloy without signs of burnout. Individual dark needle-like phases and single pores were noted. The conditions of dispersed Si precipitations, $Al_{32}Si_{10}Fe_5Mn$ and $Al_{37}Si_5Fe_5Mn$ chipping, as well as the separation of the $Al_{36}Si_3Fe_6Mn_3$ phase in skeletal form were described. The advantages of the microstructure of ingots samples from manufacturer No. 1 were listed. It corresponded to the modified state of the AK9ch alloy. The branches of dendrites and the sizes of silicon inclusions were smaller. Needle-like phases of $Al_xSi_yFe_zMn_q$ were not detected.

Discussion and Conclusion. Light areas in the castings fractures were formed by a brittle fracture mechanism, which is due to the presence of $Al_xSi_yFe_zMn_q$ phase plates in the alloy structure. If iron-containing phases are inherited from the source material, then traditional methods of suppressing formation do not lead to the creation of compact equiaxed polyhedra. To improve the quality of castings, it is recommended to use ingots with a pre-modified structure, without including phase plates of variable composition $Al_xSi_yFe_zMn_q$. The results obtained can be used, among other things, to justify the requirements for the material during tenders, which will enable the enterprises of the machine-building industry to improve the quality of products and reduce the cost of marriage. As a result, this will increase their competitiveness in the Russian and world markets.

Keywords: brittle plates of the iron-containing phase, Al-Si-Mg system alloy, structure-modified ingots, charge quality

Acknowledgements: the authors would like to thank the Editorial Board of the Journal and the Reviewer for attentive attitude to the article and suggestions made that helped to improve its quality.

For citation. Muratov VS, Kazakov MS. Influence of the Structural-Phase Composition of the Initial Charge Material on the Qualitative Characteristics of Castings from Al-Si-Mg System Alloy. *Safety of Technogenic and Natural Systems.* 2023;7(3):66–76. https://doi.org/10.23947/2541-9129-2023-7-3-66-76

Научная статья

Влияние структурно-фазового состояния исходного материала шихты на качественные характеристики отливок из сплава системы Al-Si-Mg

В.С. Муратов, М.С. Казаков ✉

Самарский государственный технический университет, г. Самара, Российская Федерация

✉Kazakov.mishel@gmail.com

Аннотация

Введение. Работа фокусируется на решении проблем качества отливок из сплава Al-Si-Mg (АК9). Отмечены отсутствие единой теории модифицирования сплавов и необходимость поиска решений, обеспечивающих хорошее качество продукции. Рассматриваются причины брака из-за слабого обоснования выбора производителя исходного шихтового материала — чушек. Чушки от двух поставщиков сравниваются с точки зрения структурно-фазового состояния. Показано, как оно обусловливает дефекты отливок. Отмечена неэффективность традиционных методов подавления образования хрупких пластин железосодержащей фазы в сплаве системы Al-Si-Mg за счет присутствия в химическом составе сплава Mn. Если указанный недостаток наследуется из исходного материала, общепринятый подход не срабатывает. Сформулированы рекомендации по решению этой выявленной проблемы. Внедрение предложенного подхода в производственную практику способно открыть путь к решению важной прикладной задачи — улучшить формулировки заданий для тендеров. Актуальность исследования обусловлена широким применением сплавов системы Al-Si-Mg (АК9) в современном машиностроении, в том числе в аэрокосмических конструкциях. Цель данной работы — изучить влияние структурно-фазового состояния исходного материала на качественные характеристики готовых отливок из сплава системы Al-Si-Mg.

Материалы и методы. Проанализированы восемь плавок, в которых использовались чушки двух производителей. Рентгенография позволила выявить корреляцию между строением излома отливок, структурой и качественными показателями. Для анализа микроструктуры и химического состава фаз использовали сканирующую электронную микроскопию. Устанавливая требования к качеству, исходили из действующих отраслевых и государственных стандартов. Из этих же документов брали условия термической обработки образцов. Спектрограммы визуализировали в виде графиков, демонстрирующих интенсивность пика элемента в оже-спектре и энергию электронов, возникших в результате оже-эффекта.

Результаты исследования. Результаты рентгенографии дают основания утверждать, что продукция, предоставляемая поставщиком № 1, обладает значимыми преимуществами в плане качества. Если ориентироваться на отраслевой стандарт, исключение из процесса чушек 2-го поставщика обеспечивает выпуск продукции без литейных дефектов на уровне 73 %. В противном случае этот показатель не превысил 57 %. Браковочными индикаторами были несплошности, скопления раковин, высокая пористость. После плавок 5–8, которые задействовали материалы 2-го производителя, исследовались изломы образцов после разрыва. Выделены локации с гладким, вязким и смешанным рельефом. Увеличение до ×500 позволило установить незначительные участки с вязким рельефом, что характерно для хрупкого разрушения по механизму скола. Установлено отсутствие включений и ликваций. Рассмотрена микроструктура шлифов из разрывных образцов. Выяснилось, что она соответствует модифицированному и термообработанному состоянию сплава АК9ч без признаков пережога. Отмечены отдельные темные игольчатые фазы и единичные поры. Описаны условия дисперсных выделений Si, выкрашивания $Al_{32}Si_{10}Fe_5Mn$ и $Al_{37}Si_5Fe_5Mn$, а также выделение фазы $Al_{36}Si_3Fe_6Mn_3$ в скелетообразной форме. Перечислены преимущества микроструктуры образцов чушек от производителя № 1. Она соответствует модифицированному состоянию сплава АК9ч. Ветви дендритов и размеры включений кремния меньше. Не обнаруживаются иглообразные фазы $Al_xSi_yFe_zMn_q$.

Обсуждение и заключение. Светлые участки в изломах отливок образовались по хрупкому механизму разрушения, что связано с наличием в структуре сплава пластин фазы $Al_xSi_yFe_zMn_q$. Если железосодержащие фазы наследуются из исходного материала, то традиционные методы подавления образования не приводят к созданию компактных равноосных полиэдров. Для повышения качества отливок рекомендуется использовать чушки с предварительно модифицированной структурой, без включения пластин фазы переменного состава $Al_xSi_yFe_zMn_q$. Полученные результаты можно задействовать в том числе для обоснования требований к материалу при проведении тендеров, что даст возможность предприятиям машиностроительной отрасли улучшить качество продукции и снизить затраты на брак. В итоге это повысит их конкурентоспособность на российском и мировом рынке.

Ключевые слова: хрупкие пластины железосодержащей фазы, сплав системы Al-Si-Mg, чушки с модифицированной структурой, качество шихты

Благодарности: авторы выражают благодарность редакционной коллегии журнала и рецензенту за профессиональный анализ и рекомендации для корректировки статьи.

Для цитирования. Муратов В.С., Казаков М.С. Влияние структурно-фазового состояния исходного материала шихты на качественные характеристики отливок из сплава системы Al-Si-Mg. *Безопасность техногенных и природных систем*. 2023;7(3):66–76. https://doi.org/10.23947/2541-9129-2023-7-3-66-76

Introduction. According to GOST 1583-93[1] alloys of the Al-Si-Mg (AK9) system belong to the first group (silumins). They are widely used in modern mechanical engineering. In aerospace structures, aluminum alloy castings account for 3–5 % of the mass [1].

The use of cast blanks in comparison with deformed semi-finished products can reduce the complexity of machining parts and increase the metal utilization factor several times [2]. In the aerospace industry, this alloy is used to produce parts that are complex in configuration, operating at medium loads and temperatures from minus 196 to plus 175 °C[2]. Main characteristics of the alloy:

– good casting properties;

– tightness;

– corrosion resistance;

– weldability;

– low density;

– relatively high modulus of elasticity;

[1] GOST 1583-93. *Aluminium casting alloys. Specifications*. Biblioteka GOSTov. URL: http://vsegost.com/Catalog/18/18745.shtml (accessed: 22.08.2023).

[2] OST 92-0920-85. *Metally i splavy tsvetnye. Marki, razreshennye k primeneniyu.* Tekhnicheskaya literatura. URL: https://booktech.ru/normativy/ost/ost-92-0920-85-metally-i-splavy-cvetnye-marki-razreshennye-k-primeneniyu.html (accessed: 22.08.2023).

– low temperature coefficient of linear expansion;

– wear resistance;

– affordable price [3–7].

The properties of silumins depend on the conditions of melting and subsequent processing [8]. An effective method of improving their structure and properties is modification with multicomponent compositions. This makes it possible to influence not only silicon, which is part of the eutectic (α+Si), but also primary silicon crystals [9–10]. Let us note the need to effectively deal with such a disadvantage of Al-Si-Mg alloys as gas absorption. For this purpose, degassing fluxes and modification at low temperatures are used [11]. Currently, there is no unified theory of modification, so the search for optimal solutions continues to ensure a high level of product quality, compliance with regulatory and design documentation [11]. The presented work is intended to partially compensate for the lack of data in this area.

Control plays a leading role in improving the quality of castings. Its tasks are:

– to exclude the ingress of defective castings for machining and assembly;

– to create conditions for critical analysis and improvement of foundry technology.

The complexity of technological processes of foundries is associated with the use of a wide range of materials. The formation of the quality of castings is determined by many factors. The most critical of them are:

– the quality of the initial molding, charge and auxiliary materials;

– the level of mechanization and automation of the technological process;

– the compliance with the technological process at all stages of production;

– the organization of production and workshop management.

Within the framework of the presented work, the reasons for the growth of waste associated with an insufficiently justified choice of the manufacturer of the charge material — ingots are analyzed. The recommendations are given to eliminate this problem. A comparative analysis of the structural and phase state of the source material from two suppliers was performed. It is shown how defects in castings of the Al-Si-Mg alloy system depend on the structural and phase state of the initial charge materials.

It should be recognized that traditional methods of suppressing the formation of brittle plates of the iron-containing phase in the alloy of the Al-Si-Mg system are ineffective due to the mandatory presence of Mn in the chemical composition of the alloy. We are talking about cases when the specified defect is inherited from the source material. The recommendations for solving this identified problem are formulated. To improve the quality of castings, it is advisable to use a charge of ingots with a pre-modified structure. It should not include phase plates of variable composition AlxSiyFezMnq.

The work objective is to study the influence of the structural-phase state of the source material on the qualitative characteristics of finished castings from the Al-Si-Mg alloy system.

Materials and Methods. According to the results of eight melts, the characteristics of castings made of AK9ch alloy were analyzed. Ingots from manufacturers No. 1 and No. 2 were used as the starting material. Ingots were melted down with waste from their own production (substandard castings made of AK9ch alloy). Table 1 provides the percentage of materials. The manufacturer is selected based on the results of competitive procurement for reasons of economic feasibility. In any case, the material must comply with GOST 1583-96. The method of manufacture is permanent-mold casting.

Table 1

Percentage (by weight) of raw materials in the general melting

Melting no.	Manufacturer no. 1	Manufacturer no. 2	Waste of own production
1	40	0	60
2	35	0	65
3	25	0	75
4	20	0	80
5	20	5	75
6	10	20	70
7	5	20	75
8	0	20	80

Chemical composition of the samples was determined by the spectral method on MFS-8 device. Mechanical properties were studied on separately cast samples (GOST 1497-84[3]) after heat treatment in T6 mode (quenching — 535 ± 5 °C, cooling in water, aging — 175 ± 5 °C). To determine the mechanical properties, a strength testing machine UTS-111.2-100-22 was used. The microstructure was studied by the cuts from wedge samples, ingots and discontinuous samples etched in Keller reagent, as well as on the fractures. The Zeiss Stemi2000-C stereoscopic microscope and Carl Zeiss AxiovertA1 metallographic microscope were used. The scanning electron microscopy method was implemented using the JED-2300 AnalysisStation microscope. The chemical composition of the phases was recorded by electron microprobe analysis. The macrostructure was evaluated on the fractures of wedge samples, as well as on the templates etched in an alkaline solution, cut from wedge samples and ingots. The presence of internal defects of castings was determined using the Ruslan-225 X-ray machine.

Results. Chemical composition of the samples from each melting is presented in Table 2.

Table 2

Results of determination of chemical composition of samples

Melting no.	Content of elements, mass. %									
	Al	Si	Mg	Mn	Fe	Cu	Zn	Ti	Zr	Be
1	Base	8.71	0.22	0.28	0.44	<0.1	<0.2	0.082	<0.1	<0,1
2		9.35	0.24	0.31	0.44	0.1	<0.2	0.097	0.03	<0,1
3		8.56	0.23	0.28	0.45	0.12	<0.2	0.06	0.03	<0,1
4		9.28	0.23	0.32	0.44	0.12	<0.2	0.1	0.03	<0,1
5		8.8	0.26	0.3	0.45	0.11	<0.2	0.065	0.03	<0,1
6		8.5	0.23	0.28	0.52	0.13	<0.2	<0.05	<0.1	<0,1
7		8.8	0.26	0.3	0.45	0.11	<0.2	0.055	0.03	<0,1
8		9.28	0.23	0.32	0.44	0.12	<0.2	<0.1	<0.1	<0,1
Requirements according to GOST 1583-93										
	Base	8–10.5	0.17–0.30	0.2–0.5	≤0.9	≤0.3	0.3	$\sum \leq 0.15$		<0.1

Data from Table 2 prove that chemical composition of the material of castings from all charges corresponds to GOST 1583-93.

The results of the mechanical properties test are presented in Table 3.

Table 3

Results of mechanical properties tests

Melting no.	$\sigma_{в}$, MPa	δ, %
1	280	9
2	280	6
3	270	7
4	280	3
5	340	6
6	290	6
7	340	6
8	290	7
Requirements according to GOST		
	≥ 235	≥ 3

[3] GOST 1497-84. *Metals. Methods of tension test*. Biblioteka GOSTov. URL: http://vsegost.com/Catalog/46/4616.shtml (accessed: 25.07.2023).

From the Table 3 it can be seen that according to the level of mechanical properties, the material of castings from all charges met the requirements of GOST 1583-93 for the T6 condition. Temporal tear resistance and elongation were compared.

X-ray radiography showed that for melts 1-4, in which there were no ingots from manufacturer No. 2, the yield of suitable products corresponding to OST 92-1165-2014 in terms of casting defects was 73 %. For melts 5–8, the yield of suitable products was 57 %. Rejection signs:

– irregularities in the form of shells;

– clusters of shells;

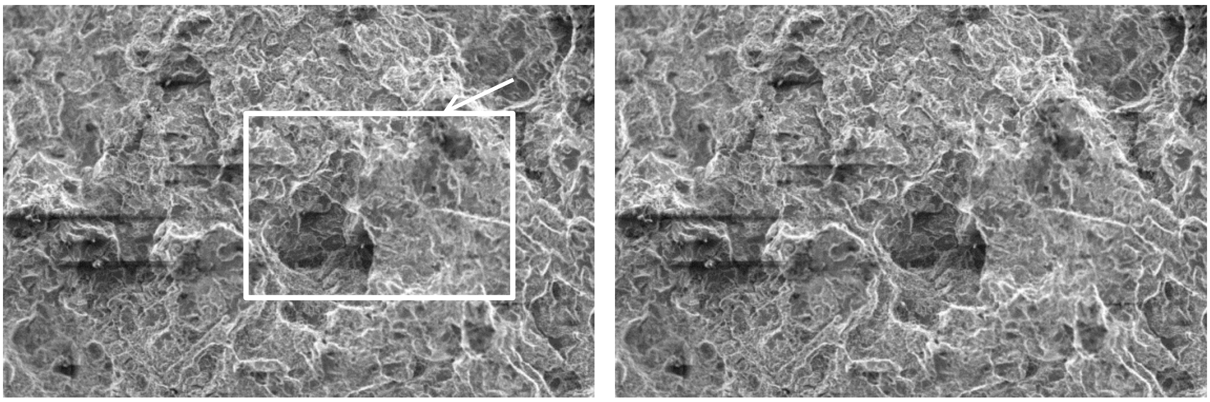
– porosity beyond the permissible level according to the X-ray standard (X-ray film obtained after X-ray inspection of the sample with a normalized porosity corresponding to a certain score[4]).

The study of the fractures of wedge samples showed that the fracture of light gray, matte, with small, light, shiny areas of various shapes and sizes was characteristic for melts 5–8 (Fig. 1).

Fig. 1. The appearance of the fracture of melts 5–8 (magnification ×6.5)

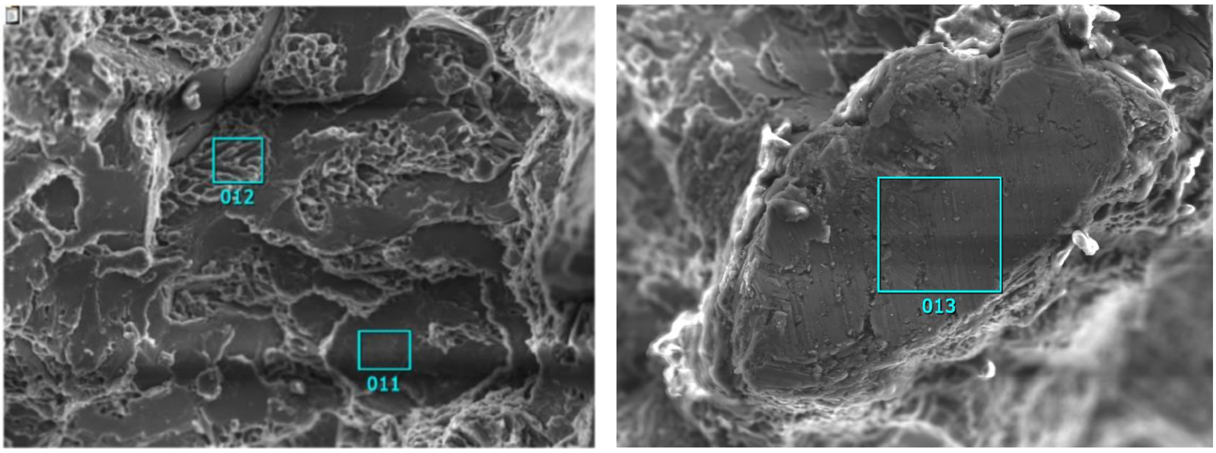
No inclusions or other defects were detected in the microstructure under the surface of the fractures, which would unambiguously cause bright, shiny areas. Porosity of 2 points according to GOST 1583-93 was observed in the macrostructure of some melts under the fracture surface. The presence of porosity did not explain the light areas in the fractures, since porosity was not observed on all wedge samples, but the appearance of all fractures was identical.

Fractures of tensile samples obtained after testing the mechanical properties of melts 5–8 were examined under an electron microscope. The bright, shiny areas (Fig. 1) corresponded to the dark area in Fig. 2 *a*. The appearance of the fracture surface at various magnifications is shown in Fig. 2.



a) *b*)

[4] OST 92-1165-75. *Castings made of aluminum alloys. Technical requirements*. Technical literature. URL: https://booktech.ru/normativy/ost/ost-92-1165-75-otlivki-iz-alyuminievyh-splavov-tehnicheskie-trebovaniya.html (accessed 21.07.2023).



c) *d*)

Fig. 2. The fracture surface of the tensile sample: *a* — general view with magnification ×50;
b — areas with smooth relief with magnification ×150; *c* — mixed relief with magnification ×200;
d — a large smoothed section of the fracture with magnification ×200

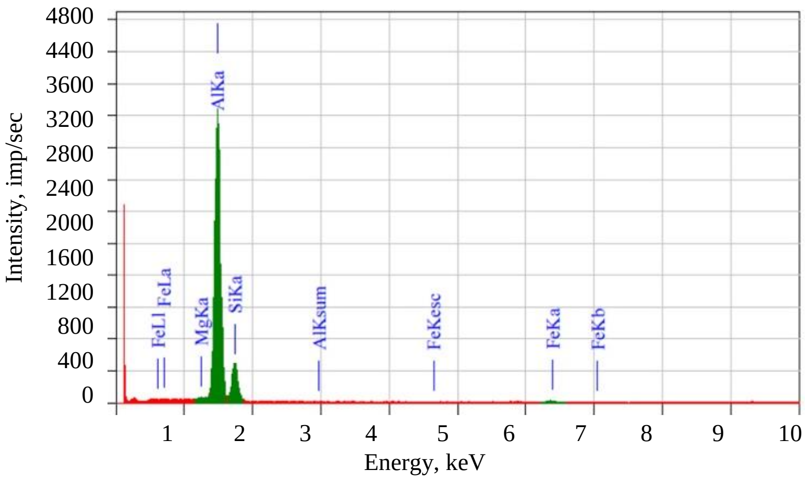
When magnified to ×500, it could be seen that the shiny areas were depressions, more often with a smoothed surface. There were minor areas with a viscous relief, which was characteristic of brittle fracture by the mechanism of chipping. The main part of the fracture surface had a viscous relief. The results of micro-X-ray spectral analysis of the fracture surface at points 11, 12, 13 (Fig. 2) are presented in Table 4. Points 11 and 13 correspond to smoothed areas, point 12 — viscous.

Table 4

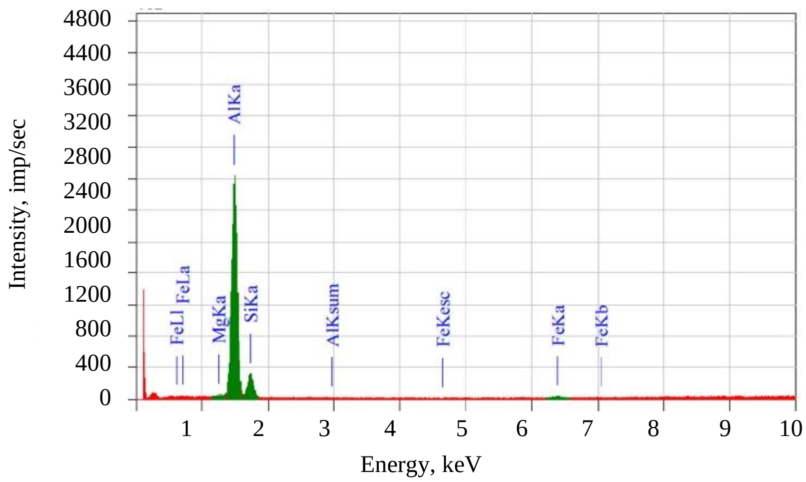
Chemical analysis of the fracture zone surface

Point no. (see Fig. 2)	Content of elements, mass. %			
	Mg	Al	Si	Fe
11	4.71	82.61	11.27	1.41
12	4.51	83.35	9.46	2.68
13	5.13	84.72	8.11	2.04

The spectrograms of the points were identical (Fig. 3). No significant differences in chemical composition were revealed between the zones with viscous and brittle smoothed relief, which indicated the absence of inclusions and liquations.



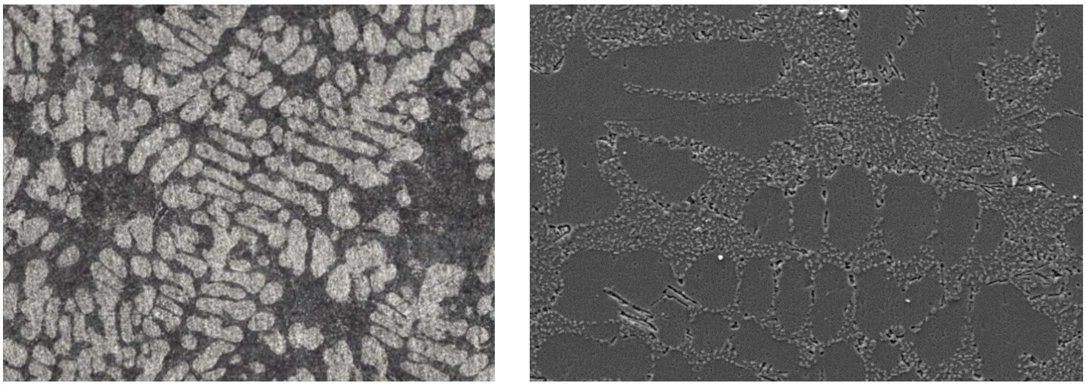
a)



b)

Fig. 3. Spectrogram of the electron microprobe analysis results of the fracture surface: *a* — point 11 from Fig. 2; *b* — point 12 from Fig. 2. Here the intensity of the peak of the element in the Auger spectrum and the energy of the electrons generated as a result of the Auger effect are shown

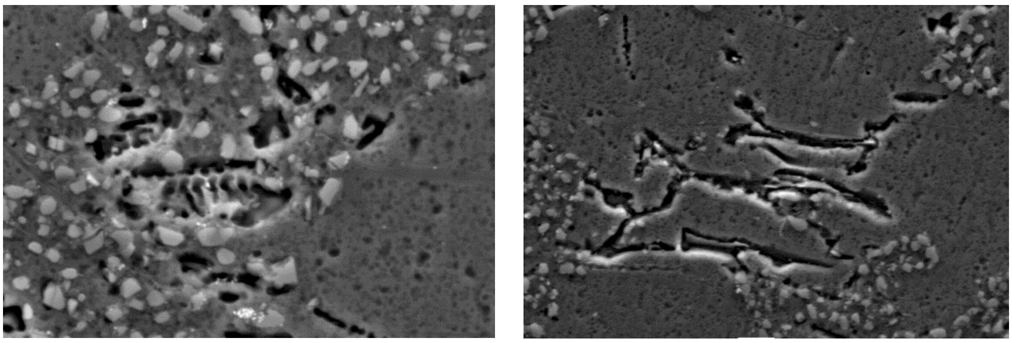
The microstructure studied on the sections made of discontinuous samples (melts 5–8) corresponded to the modified and heat-treated state of the AK9ch alloy without signs of burnout (Fig. 4 *a*). Separate dark needle-like phases and single pores were observed. The main phase components of the microstructure were clearly visible under an electron microscope (Fig. 4 *b*).



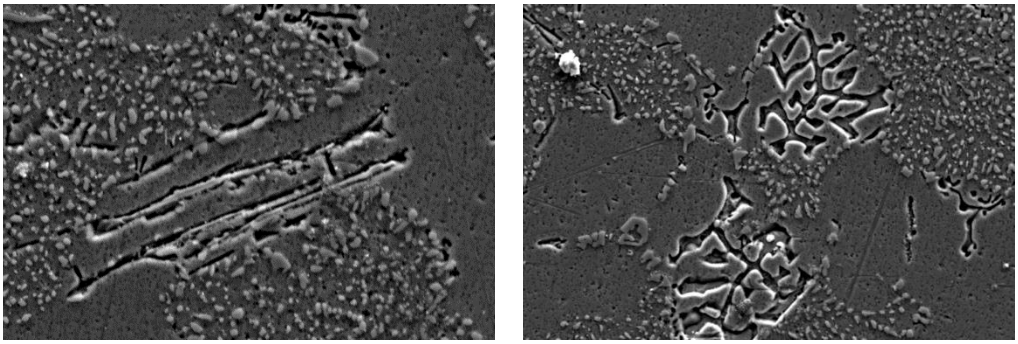
a) *b*)

Fig. 4. Appearance of the microstructure: *a* — light optical microscopy with magnification ×200; *b* — electron microscopy with magnification ×250

The data of electron microscopy and electron microprobe analysis made it possible to determine the main phases: α (light zones), α+Si (dark zones). In the α+Si phase, dispersed Si precipitations of less than 5 microns in size were observed (Fig. 5 *a*). Electron microprobe analysis showed that $Al_{32}Si_{10}Fe_5Mn$ and $Al_{37}Si_5Fe_5Mn$ (Fig. 5 *b*, 5 *c*) were partially crumbled during grinding and polishing (Fig. 5 *c*). The separation of $Al_{36}Si_3Fe_6Mn_3$ phase in a skeletal form was also observed (Fig. 5 *d*).



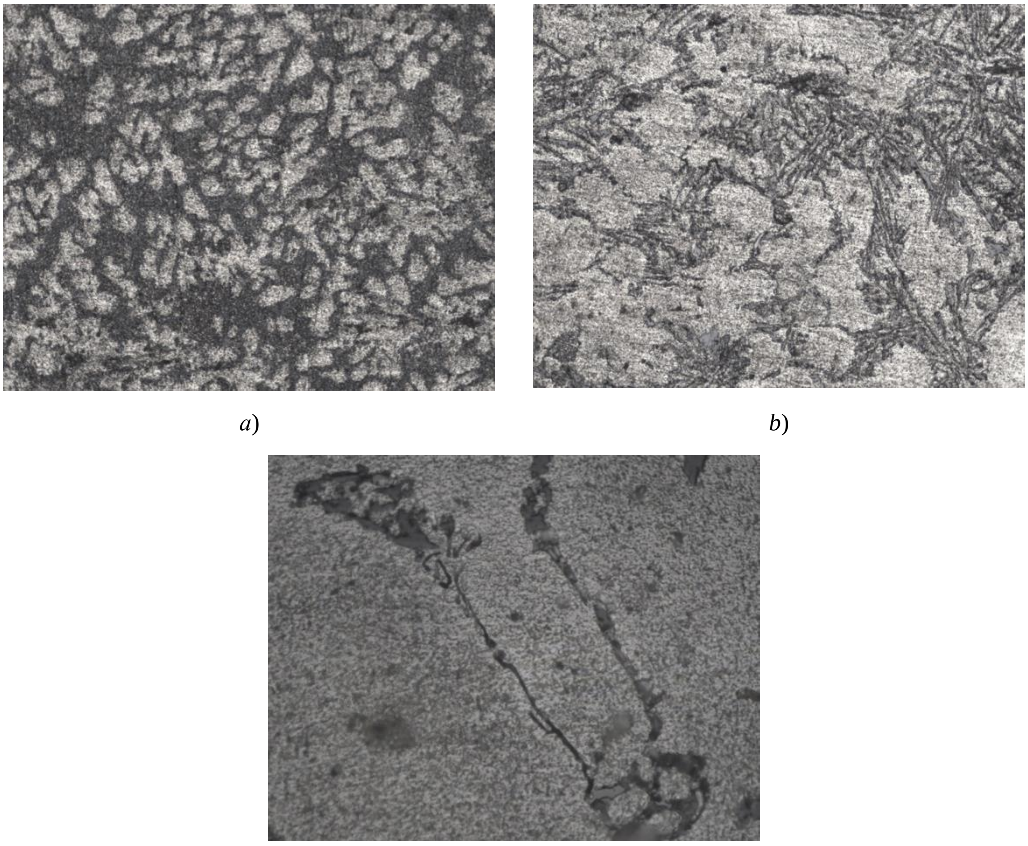
a) *b*)



c) *d*)

Fig. 5. Microstructure of melting samples (5–8): *a* — separation of silicon with magnification ×2000; *b* — phases $Al_{32}Si_{10}Fe_5Mn$ and $Al_{37}Si_5Fe_5Mn$ with magnification ×1000; *c* — chipping of brittle plates of phases $Al_{32}Si_{10}Fe_5Mn$ и and $Al_{37}Si_5Fe_5Mn$ with magnification ×750; *d* — phase $Al_{36}Si_3Fe_6Mn_3$ in skeletal form with magnification ×500

The microstructure of the ingot samples from manufacturer No. 1 corresponded to the modified state of the AK9ch alloy. The branches of the dendrites were significantly smaller than in the sample of the ingot from supplier No. 2. The sizes of silicon inclusions were up to 4 microns. They were homogeneous and had a globular appearance. The main phases were α and α+Si (Fig. 6 *a*). Needle-like phases of $Al_xSi_yFe_zMn_q$ were not found in the structure of ingot samples from manufacturer No. 1.



a) *b*) *c*)

Fig. 6. The microstructure of the initial ingot: *a* — manufacturer No. 1, 70 microns with magnification ×500; *b* — manufacturer No. 2, 70 microns with magnification ×500; *c* — plate phase in the microstructure of the ingot from manufacturer No. 2, 20 microns with magnification ×1000

The microstructure of the ingot sample from supplier No. 2 corresponded to the unmodified state of the AK9ch alloy. The branches of dendrites were large. Silicon inclusions were needle-shaped and large. The main phases were α and α+Si (Fig. 6 *b*). Phases in the form of dark needle-like inclusions were observed (Fig. 6 *c*).

The analysis of the results of the study suggests that the structural-phase composition of the alloy determines the presence of shiny areas in the fracture of samples from melts 5–8. These are areas with smoothed relief — the results of brittle destruction. The most probable cause of this phenomenon is the presence of zones with coarse needle-like precipitation, which are brittle $Al_xSi_yFe_zMn_q$ plates with a pronounced interface. During stretching or other destructive tests, these precipitations act as concentrators (breaks in the metal). Accordingly, when the crack development front goes through them, they chip off. Let us explain. Lamellar precipitates are solid and poorly retained in the base metal. In the process of grinding and polishing the samples, they crumble, leaving cavities with smooth walls. In their place are smooth areas that shine in the fracture. It can also be assumed that these phases are stable in the melt (do not dissolve in the matrix). When cooled, they will act as crystallization centers and provoke the formation of defects, since they are sharp stress concentrators.

Silicon crystallizes in the form of small spherical particles, so it can be stated that the modifier used is effective for influencing silicon, which is part of the eutectic (α+Si). At the same time, an adjustment of the technological process is required to influence the needle phases of $Al_xSi_yFe_zMn_q$. With the introduction of 0.2–0.5 % Mn, as a rule, it is possible to suppress the formation of brittle plates of $Al_xSi_yFe_zMn_q$ phase. However, in the studied melts (5–8), despite the Mn content of 0.28–0.32 %, this phase persists, since it is inherited from the source material.

Discussion and Conclusion. Based on the results of the conducted scientific research, three main conclusions can be drawn.

1. The structural-phase state of the source material is inherited in castings and in the presence of iron-containing phases in the form of brittle plates can negatively affect the quality characteristics of cast blanks.

2. The light areas in the castings' fractures are areas with smoothed relief. They were formed as a result of brittle fracture, which is due to the presence of a variable composition of $Al_xSi_yFe_zMn_q$ in the structure of brittle phase plates.

3. The presence of Mn alloy in the chemical composition does not always suppress the formation of brittle plates of the iron-containing phase. If it is inherited from the source material, this traditional approach does not work and compact equiaxed polyhedra with a weaker negative influence are not formed. To improve the quality of castings, it is recommended to use ingots with a pre-modified structure in the charge, in which there are no inclusions of plates of the phase of variable composition $Al_xSi_yFe_zMn_q$.

References

1. Polmear Ya. *Legkie splavy: ot traditsionnykh do nanokristallov*. Moscow: Tekhnosfera; 2008. 464 p. URL: https://www.technosphera.ru/lib/book/72?read=1 (accessed: 26.06.2023).

2. Zolotorevskii VS, Belov NA. Metallovedenie liteinykh alyuminievykh splavov. Moscow: MISiS; 2005. 376 p. URL: https://e.lanbook.com/book/2055 (accessed: 26.06.2023).

3. Wei Yan, Weiqing Chen, Senlin Zhang, Bing Li, Jing Li. Evolution of solidification structures and mechanical properties of high-Si Al alloys under permanent magnetic stirring. *Materials Characterization*. 2019;157:109894. https://doi.org/10.1016/j.matchar.2019.109894

4. Makhlouf MM, Guthy HV. The aluminum–silicon eutectic reaction: mechanisms and crystallography. *Journal of Light Metals*. 2001;1(4): 199–218. https://doi.org/10.1016/S1471-5317(02)00003-2

5. Haizhi Ye. An overview of the development of Al-Si alloy based material for engine applications. *Journal of Materials Engineering and Performance*. 2003;12:288–297. https://doi.org/10.1361/105994903770343132

6. Afanasev VK, Popova MV, Prudnikov AN. Effect of hydrogen on the structure and properties of eutectic silumin with 15% silicon. *Metallovedenie i termicheskaya obrabotka metallov*. 2022;(6):10–16. https://doi.org/10.30906/mitom.2022.6.10-16

7. Sathyapal Hegde, K. Narayan Prabhu. Modification of eutectic silicon in Al-Si alloys. *Journal of Materials Science*. 2008;43:3009–3027 https://doi.org/10.1007/s10853-008-2505-5

8. Kuznetsov AO, Shadayev DA, Konkevich VYu, Bochvar SG, Kunyavskaya TM. Modification of silumins: different approaches for one alloying system. *Tekhnologiya legkikh splavov*. 2014;(4):75–81.

9. Napalkov VI, Makhov SV, Pozdnyakov AV. Modifitsirovanie alyuminievykh splavov. Moscow: MISiS; 2017. 347 p. URL: https://e.lanbook.com/book/117172 (accessed: 26.06.2023).

10. Jing Zhang, Hongmei Chen, Hui Yu, Yunxue Jin. Study on dual modification of Al-17%Si alloys by structural heredity. *Metals*. 2015;5(2):1112–1126 https://doi.org/10.3390/met5021112

11. FQ Zu, Li Xiaoyun. Functions and mechanism of modification elements in eutectic solidification of Al-Si alloys. *China Foundry*. 2014;11(4):287–309 URL: https://www.researchgate.net/publication/274634943_Special_Report_CHINA_FOUNDRY_Functions_and_mechanism_of_modification_elements_in_eutectic_solidification_of_Al-Si_alloys_A_brief_review (accessed: 26.06.2023).

Received 01.07.2023
Revised 26.07.2023
Accepted 03.08.2023

About the Authors:

Vladimir S. Muratov, Dr. Sci. (Eng.), Professor of the Metallurgy, Powder Metallurgy, Nanomaterials Department, Samara State Technical University (244, Molodogvardeyskaya St., Samara, 443100, RF), ResearcherID, ScopusID, ORCID, muratov1956@mail.ru

Mikhail S. Kazakov, Postgraduate Student of the Metallurgy, Powder Metallurgy, Nanomaterials Department, Samara State Technical University (244, Molodogvardeyskaya St., Samara, 443100, RF), ResearcherID, ORCID, kazakov.mishel@gmail.com

Claimed contributorship:

VS Muratov: academic advising; research results analysis; revision of the text; conclusions correction.

MS Kazakov: formulation of the basic concept, goals and objectives of the study; testing; analysis; control; text preparation; conclusions formulation.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Об авторах:

Владимир Сергеевич Муратов, доктор технических наук, профессор кафедры металловедения, порошковой металлургии, наноматериалов Самарского государственного технического университета (443100, РФ, г. Самара, ул. Молодогвардейская, 244), ResearcherID, ScopusID, AuthorID, ORCID, muratov1956@mail.ru

Михаил Сергеевич Казаков, аспирант кафедры металловедения, порошковой металлургии, наноматериалов Самарского государственного технического университета (443100, РФ, г. Самара, ул. Молодогвардейская, 244), ResearcherID, ORCID, kazakov.mishel@gmail.com

Заявленный вклад соавторов:

В.С. Муратов — научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

М.С. Казаков — формулирование основной концепции, целей и задач исследования, проведение испытаний, анализ, контроль, подготовка текста, формулирование выводов.

Поступила в редакцию 01.07.2023
Поступила после рецензирования 26.07.2023
Принята к публикации 03.08.2023

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.