

Study of the deformability of AK7 alloy

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Simulations using the DEFORM software have shown that during hot rolling of cast billets made of AK7 alloy with a total reduction of more than 36.7%, there is a high probability of cracking, whereas heat-treated specimens can be deformed to the same extent without cracking. These results were confirmed by a physical experiment conducted using the hot rolling method. Studies of the microstructure of wheel blanks produced by low-pressure die casting have shown that heat treatment under the following conditions: heating to 540 °C, holding for 6 hours, and air cooling, leads to a change in shape as well as a reduction in the size of eutectic silicon due to fragmentation and spheroidization, which increases the alloy's ductility by approximately twofold. Industrial testing showed that when rolling 19-inch wheel rims with a total reduction of 44.1%, the yield of usable parts was 40% for wheels rolled in the as-cast condition, whereas no cracks were observed in the heat-treated blanks after rolling, and the yield of usable parts reached 100%.

Key words: AK7 aluminum alloy, wheel rims, rolling, silumin, hot rolling, formability of silumins, computer simulation, heat treatment, degree of reduction, microstructure.

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Introduction

Recently, there has been a trend toward using cast aluminum alloys as materials capable of undergoing plastic deformation. This makes it possible to produce complex-shaped castings and then strengthen them through subsequent deformation. An example of the practical application of this combination is the technology for manufacturing automotive wheel rims made of silumin, such as the AlSi7Mg alloy [1, 2]. The AK7 alloy is a cast aluminum alloy of the Al–Si–Mg system and possesses a number of advantages, including high flowability, minimal shrinkage, and good machinability, which ensures its use in various industrial sectors. In its cast state, the alloy is used in the automotive industry for the manufacture of housings and other internal combustion engine components [3], while the aviation industry uses AK7 alloy for the production of parts with high structural strength [4, 5]. However, the deformability of this alloy remains poorly studied, so this research should be considered relevant.

The list of problems associated with the deformability of cast aluminum alloys includes a tendency to crack, low ductility in the as-cast state, and microstructural non-uniformity, which limits their use under conditions of intense mechanical stress [6–8]. Research in this field is focused on developing new methods of heat treatment, modification, and alloying that will improve the structure and properties of cast alloys [9, 10].

In the as-cast state, the microstructure of the AK7 alloy consists of dendrites of an aluminum-based α -solid

solution and a eutectic phase composed of an α -solid solution and silicon crystals [11–13]. The Al – Si eutectic provides high casting properties, such as flowability and low shrinkage; however, the platelet shape of silicon in the eutectic reduces the alloy's mechanical properties, particularly its ductility [14]. To improve the alloy's structure, modifications are applied, for example, with titanium, lanthanum, or strontium, which leads to the refinement of the silicon phase and an increase in strength [15, 16]. Heat treatment, including quenching and aging, allows for the stabilization of a supersaturated solid solution and the precipitation of dispersed strengthening phases, which significantly improves the strength characteristics of AK7 [17, 18]. Furthermore, research results [19–21] show that the structure of Al–Si–Mg aluminum alloys depends on the cooling rate and composition, which influences their deformation properties.

The main issues with the formability of AK7 are related to structural heterogeneity, the presence of large silicon crystals and intermetallic compounds, as well as a tendency to form microcracks during deformation. It has been noted [22, 23] that the deformation of cast aluminum alloys is accompanied by an increase in dislocation density, leading to a decrease in fatigue strength. In addition, the high silicon content in the eutectic promotes brittle fracture of the alloys, especially under dynamic loads [24, 25].

Various approaches have been proposed to address these issues, including the optimization of heat treatment conditions, the use of intensive plastic deformation methods, and the development of new alloy compositions [26, 27]. However, the lack of comprehensive studies that

account for the relationship between microstructure, deformation conditions, and process parameters limits the implementation of such solutions in production.

Therefore, the aim of this study is to determine the optimal compaction conditions for rolling an automotive wheel rim from an AK7 alloy billet produced by low-pressure die casting.

To achieve the stated objective, the following tasks were addressed in this study:

- to investigate the microstructure of the AK7 alloy in its as-cast and heat-treated states, both before and after deformation;
- to perform computer simulations of the hot rolling of wheel rims made of cast and heat-treated AK7 alloy blanks;
- perform physical modeling of the hot rolling of blanks cut out of cast wheel blanks at the initial and heat-treated states.

Materials and methods

The initial material was a 100 mm long, 50 mm wide, and 17 mm thick blank made of AK7 alloy, cut out from the rim of a car wheel cast at a Russian metallurgical plant using the low-pressure die-casting method (Fig. 1).

The chemical composition of the AK7 alloy template is shown in Table 1.

Physical modeling of rim rolling was performed using hot rolling under laboratory conditions at Siberian Federal University on a DUO-330 rolling mill. Prior to rolling, the blank was cut into billets, which were milled to thicknesses of 12, 13, 15, and 17 mm on a JET BD-12G turning and milling machine, with two billets prepared for each thickness. Half of the blanks—one for each thickness—were

left in their original state, while the other half underwent heat treatment under the following conditions: heating to 540 °C, holding for 6 hours, and air cooling. The heat treatment was performed in a LAC muffle furnace.

The rolling temperature was 425 °C, which corresponds to the temperature conditions of industrial rolling. Preheating prior to rolling was performed in a SNO-3.6.2/10I2-type resistance electric furnace. The rolling pattern corresponded to the compression conditions used in industrial rolling and is shown in Table 2.

Computer simulations of hot rolling were performed using the DEFORM-3D software package.

Microsections were prepared on a Struers Tegramin-30 automated grinding and polishing machine. For structural analysis, an anisotropic oxide film was applied to the prepared micro-sections using the Struers LECTROPOL-5 electrolytic polishing and etching system. Metallographic examinations were performed on a Carl Zeiss Axio Observer 7 Mat optical microscope with the Thixomet.Pro analysis software package.

Tensile mechanical property tests were conducted in accordance with GOST 1497–84 on a Walter+Bai AGLFM universal testing machine.

Results and discussion

Computer simulations were performed using the parameters and boundary conditions presented in Table 3. Simulations of hot rolling in the as-cast condition were based on data from [28], which utilized rheological data for A356, an alloy analogous to AK7. To simulate the hot rolling of heat-treated AK7 alloy specimens, the rheological parameters determined for it in the work [29].

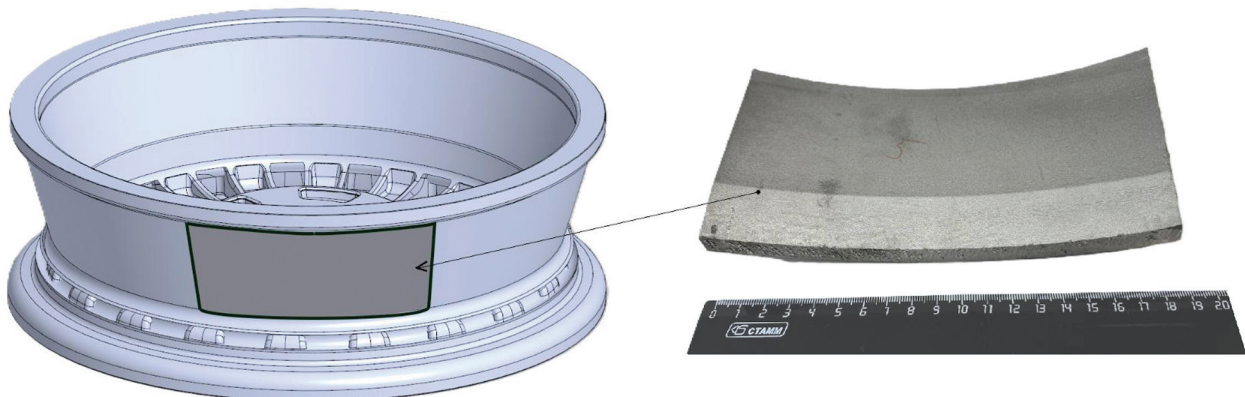


Fig. 1. Model of a cast wheel disc blank made of AK7 alloy and a template cut out of it (the arrow indicates the cutout location)

Table 1
Chemical composition of AK7 alloy, % (by mass)

Chemical element	Si	Mg	Fe	Ti	Mn	Zn	Cu	Al
Composition in accordance with GOST 1583–93	6.0–8.0	0.2–0.5	0.0–1.3	–	0.2–0.6	0.0–0.5	0.0–1.5	Rest
Actual composition	6.93	0.23	0.09	0.10	0.2	0.01	0.003	Rest

Simulations using the Cockcroft-Latam failure criterion revealed that hot rolling of cast billets with total reduction ratios of 36.7% and 44.1% results in a high probability of defect formation, a finding confirmed by physical simulations. **Fig. 2** shows that crack nucleations appear on the side surface of cast specimens rolled with an overall reduction of 36.7%, the size of which increases after an overall reduction of 44.1%, and cracks also appear in the plane. At the same time, the heat-treated specimens were rolled to the same degree of deformation without cracking, which indicates a sufficient plasticity margin for this material condition.

Table 2
Hot rolling patterns for AK7 alloy billets

No. of the passage	Reduction in thickness, mm	Draft, %	Overall reduction, %	Thickness, mm
Initial thickness 12 mm				
1	1	8.3	8.3	11
2	1	9.1	16.7	10
3	0.5	5.0	20.8	9.5
Initial thickness 13 mm				
1	1.5	11.5	11.5	11.5
2	1	8.7	19.2	10.5
3	1	9.5	26.9	9.5
Initial thickness 15 mm				
1	2	13.3	13.3	13
2	2	15.4	26.7	11
3	1.5	13.6	36.7	9.5
Initial thickness 17 mm				
1	2.5	14.7	14.7	14.5
2	2.5	17.2	29.4	12
3	2.5	20.8	44.1	9.5

Table 3
Simulation parameters for hot rolling of AK7 alloy

Parameter	Value
Length of the roller barrel, mm	540
Roller diameter, mm	330
Angular roller speed, rpm	25
Initial temperature of the blank, °C	425
Initial temperature of the rolls, °C	25
Ambient temperature, °C	25
Initial thickness of the blank, T, mm	12, 13, 15, 17
Overall dimensions of the blank (length, width, thickness)	110×50×T
Initial number of grid elements in the blank, pcs.	70000
Minimum grid element size of the blanks, mm	0.5
Tool feed rate, s/step	0.01
Roller material	AISI H-13
Blank material	Set manually based on reological research data
Efficient of convective heat exchange, N/sec/mm/°C	1 when moving the workpiece, 11 during the rolling process
Friction conditions	Friction coefficient (according to Siebel): 0.4

Thus, the physical experiment confirmed the results of the computer simulation, and its findings demonstrate the feasibility of producing defect-free products when rolling an automotive wheel rim made of AK7 alloy with an overall reduction of up to 44.1% following preliminary heat treatment. An explanation may also be found in the results of the mechanical property tests of the samples in their as-received condition and after rolling, shown in **Table 4**, which indicate that after heat treatment, the relative elongation of the billets increased approximately twofold.

In the microstructural study, samples in the as-cast and heat-treated states were used, both before and after rolling (**Fig. 3**). In the structure of the samples after casting, eutectic colonies are located in the interdendritic spaces of the aluminum-based α solid solution, and silicon in the eutectic is mainly in a platelet form (**Fig. 3, a**). The composition of the eutectic ($\alpha(\text{Al}) + \text{Si}$) also contains iron-bearing inclusions of the π phase ($\text{Al}_8\text{FeMg}_3\text{Si}_6$) in a platelet form and the β phase (Al_5FeSi) in the form of needle-like crystals.

Changes in the properties of silumin castings depending on the casting method and heat treatment regimen can be attributed to changes in the microstructure. It is known [13, 14] that during heat treatment of ingots at 300 °C for 2-4 hours, the number and morphology of phases of crystallization origin change only slightly. An increase in the annealing temperature increases the diffusion mobility of silicon atoms and promotes processes leading to a change in the shape of the phases. During high-tem-

perature heating, the solid solution may become homogenized in terms of chemical composition, and the shape and size of eutectic silicon may change due to fragmentation

and spheroidization processes. Therefore, to achieve the best effect ensuring the spheroidization of silicon, it is advisable to perform the heat treatment for hardening near the equilibrium solidus temperature. Based on this, the following heat treatment regimen was selected for the AK7 alloy in this study: heating to 540 °C, holding for 6 hours, and air cooling. As a result, the shape of the eutectic silicon crystals approaches spherical (Fig. 3, b), while the π ($\text{Al}_8\text{FeMg}_3\text{Si}_6$) and β (Al_5FeSi) phase inclusions show virtually no change in shape. Quantitative analysis of the investigated structural parameters showed that the sphericity coefficient of the silicon crystals increased to 0.8,

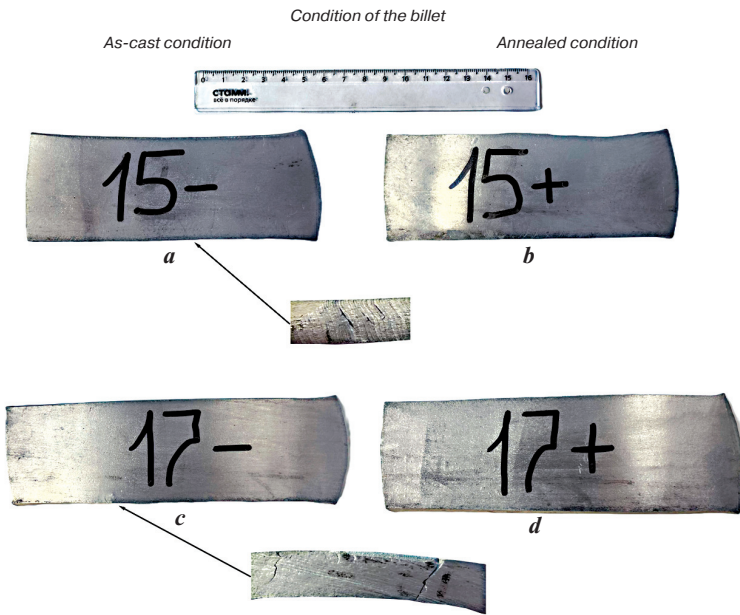


Fig. 2. AK7 alloy billets after hot rolling in the as-cast and heat-treated conditions with overall reduction of 36.7% (a, b) and 44.1% (c, d); the arrows indicate the locations of cracks on the side surfaces of the as-cast billets

Table 4
Mechanical properties of AK7 alloy billets

Condition	Mechanical properties	
	σ_B , MPa	δ , %
As-cast state before rolling	165 ± 5	5 ± 1
As-cast state after rolling with an overall reduction of 44.1%	220 ± 5	3 ± 1
Heat-treated before rolling	180 ± 5	11 ± 1
Heat-treated after rolling with an overall reduction of 44.1%	295 ± 5	9 ± 1

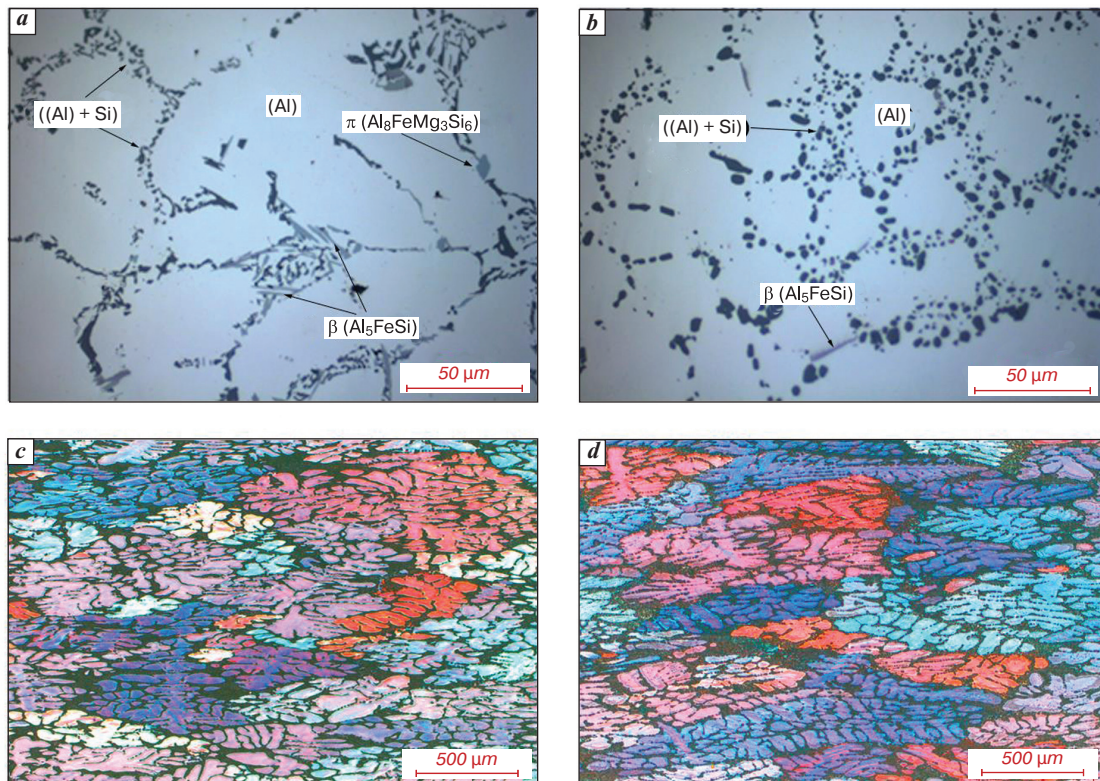


Fig. 3. Microstructure of an AK7 alloy blank: a – as-cast state; b – heat-treated state; c – as-cast state after rolling with a overall reduction of 44.1%; d – heat-treated after rolling with an overall reduction of 44.1%

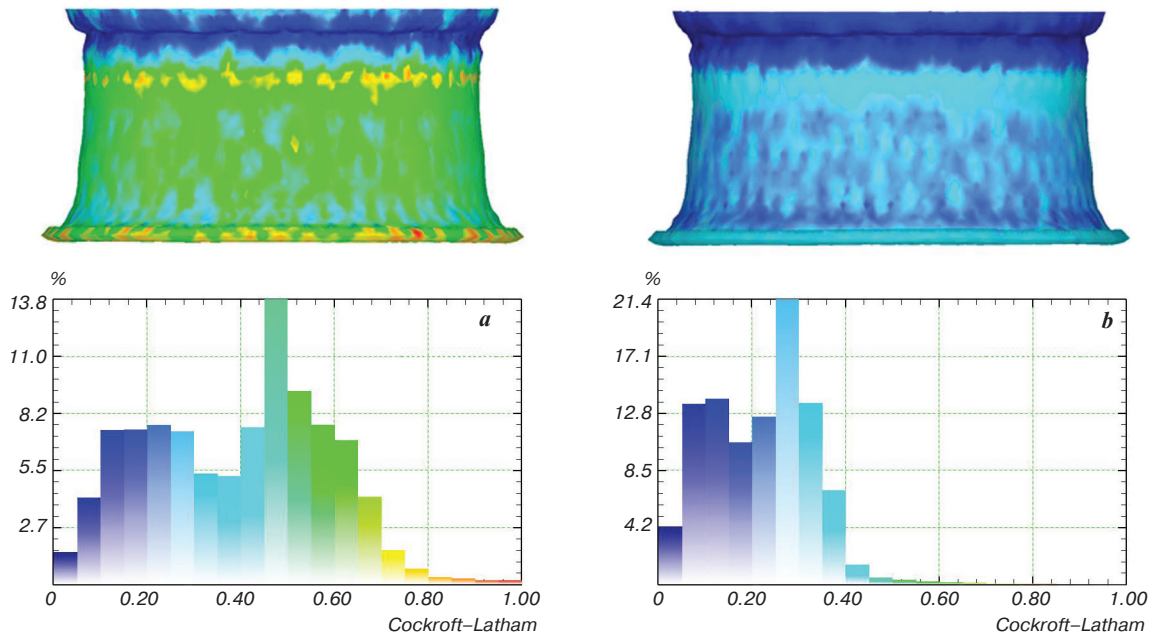


Fig. 4. Distribution of the Cockroft–Latham criterion values across the rim surface of a cast (*a*) and heat-treated (*b*) wheel blank, obtained by simulating the rolling process in the DEFORM software

while their maximum size decreased from 37 ± 1 to $13 \pm 1 \mu\text{m}$. After rolling with a compression of 44.1%, the grains of the aluminum solid solution elongated in the direction of deformation (**Fig. 3, c, d**).

Simulation of the wheel rim rolling process showed that, according to the Cockroft–Latham criterion, the risk of cracking in a cast wheel blank arises both at the rim edges and across its surface at a reduction of 36.7%, **Fig. 4, a**. Whereas a heat-treated wheel blank can be rolled with a deformation rate of 44.1%, **Fig. 4, b**. At the same time, judging by the histogram showing the distribution of the Cockroft–Latham criterion across the wheel rim surface, shown in Figure 4, b, the AK7 alloy retains sufficient plasticity even after rolling, which can compensate for both a slight increase in the degree of compression, up to approximately 50%, and a possible decrease in the blank temperature.

To validate the results of the virtual and physical experiments, an industrial trial was conducted on the rolling of 19-inch wheel rims. Twenty wheels were prepared for rolling, including 10 wheels without heat treatment and 10 wheels after heat treatment under the following conditions: heating to 540 °C, holding for 6 hours, and air cooling. The initial rim thickness was 19.2 mm, 17 mm after milling, and rolling was performed down to a thickness of 9.5 mm, corresponding to a total reduction of 44.1%. As a result of the experiment, cracks were observed on most of the wheels rolled immediately after casting, and the yield rate was 40%. No cracks were observed on the heat-treated blanks after rolling.

Conclusions

1. Studies of the microstructure of AK7 alloy wheel blanks produced by low-pressure die casting have shown

that heat treatment under the following conditions: heating to 540 °C, holding for 6 hours, and air cooling, leads to a change in the shape and dimensions of eutectic silicon due to fragmentation and spheroidization processes, which increases the alloy's ductility by approximately twofold.

2. Using computer simulation in the DEFORM software package and the Cockroft–Latham failure criterion, it was found that during hot rolling of cast billets with an overall reduction of more than 36.7%, there is a high probability of cracks forming, whereas no cracks were observed in heat-treated specimens after rolling to the same degree of deformation. The results obtained were confirmed by a physical experiment conducted using the hot rolling method.

3. Industrial testing showed that when rolling 19-inch wheel rims with an overall reduction of 44.1%, the yield rate for rims rolled in the as-cast condition was 40%, whereas no cracks were observed in heat-treated blanks after rolling, and the yield rate reached 100%.

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