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DEVELOPMENT OF NEW ALUMINUM ALLOYS FOR AUTOMOTIVE WHEEL CASTING

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ABSTRACT

This article examines the properties of new aluminum alloys based on the Al-Si-Mg system with different Mg contents for eutectic silumins. The data obtained was used for computer modeling on ProCAST software of the low-pressure casting of automotive wheels from new and serial alloys. The quality of the castings was subsequently analyzed. It was established that eutectic silumins with a Mg content of 0.25% has the best performance properties combination. Introducing these findings into industrial processes will increase efficiency to 5%.

Keywords: magnesium-containing eutectic silumin, casting and strength properties, low-pressure casting of automotive wheels.

INTRODUCTION

Heat treatment leads to hypoeutectic AlSi7Mg0.3 silumin acquiring some rather high strength properties, which gives it an advantage over the non-thermally-hardenable eutectic AlSi11 silumin. However, the relatively low technological properties give wheels cast from the AlSi7Mg0.3 alloy the following drawbacks: 1) increased thickness of excess metal, which leads to an increased amount of shavings; 2) yield decrease due to the creation of shrinkage porosity (rejection of wheels during X-ray inspection or leak testing); 3) low performance properties of automotive wheels on impact due to low plastic properties and an increased amount of shrinkage pores.

AlSi7Mg0.3 alloy's casting properties usually increase due to the overheating of a melt and the slow cooling process while casting near the hub. However, as the final result, metal overheating leads to a greater amount of shrinkage, with all the associated consequences.

Castings produced from eutectic AlSi11 silumin have practically no such casting problems because the high Si content has a positive effect on casting properties [1, 2]. However, automotive wheels made from this non-heat-hardenable alloy do not meet the high strength requirements imposed by customers.

LLC "LMZ "SKAD"" used the sophisticated AlSi11 alloy to develop a new heat-hardenable eutectic silumin notable for high casting and strength properties (patent No. 2616734).

SKAD, a casting and mechanical plant is a leading Russian enterprise specializing in the production of aluminum alloy wheels. SKAD is certified as per ISO international quality standards. All wheels produced by the company undergo an independent inspection by TÜV SÜD Automotive GMBH. The SKAD wheels are approved for operation in the USA and Western Europe, and perfectly cope with Russian conditions. The company delivers wheels to the largest automobile manufacturers like FORD, Mitsubishi, Volkswagen, etc. [3].

STUDY OF THE CASTING PROPERTIES OF NEW SILUMINS

Four pilot batches of wheels with different Mg contents were cast for the study. We applied the AlTi5B1 bar master alloy to modify a solid solution and the AlSr10 master alloy to modify an eutectic. The chemical compositions of these pilot alloys are presented in Table-1. According to the spectrometer certificate, the Mg error does not exceed 0.013%.

Table-1. Chemical composition of the pilot alloys.

Pilot alloy No.	Chemical elements, %					
	Si	Mg	Ti	Sr	Fe	B
1	11.0	0.13	0.114	0.019	0.139	0.0026
2	11.0	0.18				
3	11.3	0.25				
4	11.1	0.33				

Two standard alloys-hypoeutectic AlSi7Mg0.3 and eutectic AlSi11 with chemical compositions given in Table-2 were also prepared for control measurements.

Table-2. Chemical compositions of standard alloys.

Alloy	Chemical elements, %					
	Si	**Mg**	**Ti**	**Sr**	**Fe**	**B**
AlSi11	11.0	0.08	0.093	0.018	0.108	0.012
AlSi7Mg0.3	6.8	0.28	0.111	0.015	0.103	0.013

The manufacturability of the alloy is interdependent on its crystallization interval, which, in turn, affects the nature of the shrinkage porosity distribution. It should be noted that the small crystallization interval of silumins makes them more inclined to generating a concentrated shrink hole, while those crystallized within a wide temperature interval give scattered shrinkage porosity. Therefore, the leak-tightness of castings in relation to gases or liquids depends largely on the alloy's crystallization parameters [4].

Figure-1 presents the cooling and heating thermograms of the alloys under study. During heating or cooling, DSC curves show substantial thermal effects and a peak corresponding to the melting and crystallization of the binary [α(Al)+Si] eutectic. The cooling thermograms provide the second peak that corresponds to the initial crystallization temperature of an aluminum α-solid solution.

The silumins with no copper additives and alloyed with magnesium in non-equilibrium crystallization conditions are notable for the ternary [α(Al)+Si+Mg_2Si] eutectic at the temperatures of 555÷558°C [5, 6]. Thermal effects associated with the melting of the ternary eutectic were observed on the thermal heating curves of the alloys under study; the AlSi11 alloy has no such peak due to its low Mg content (Figure-1a).

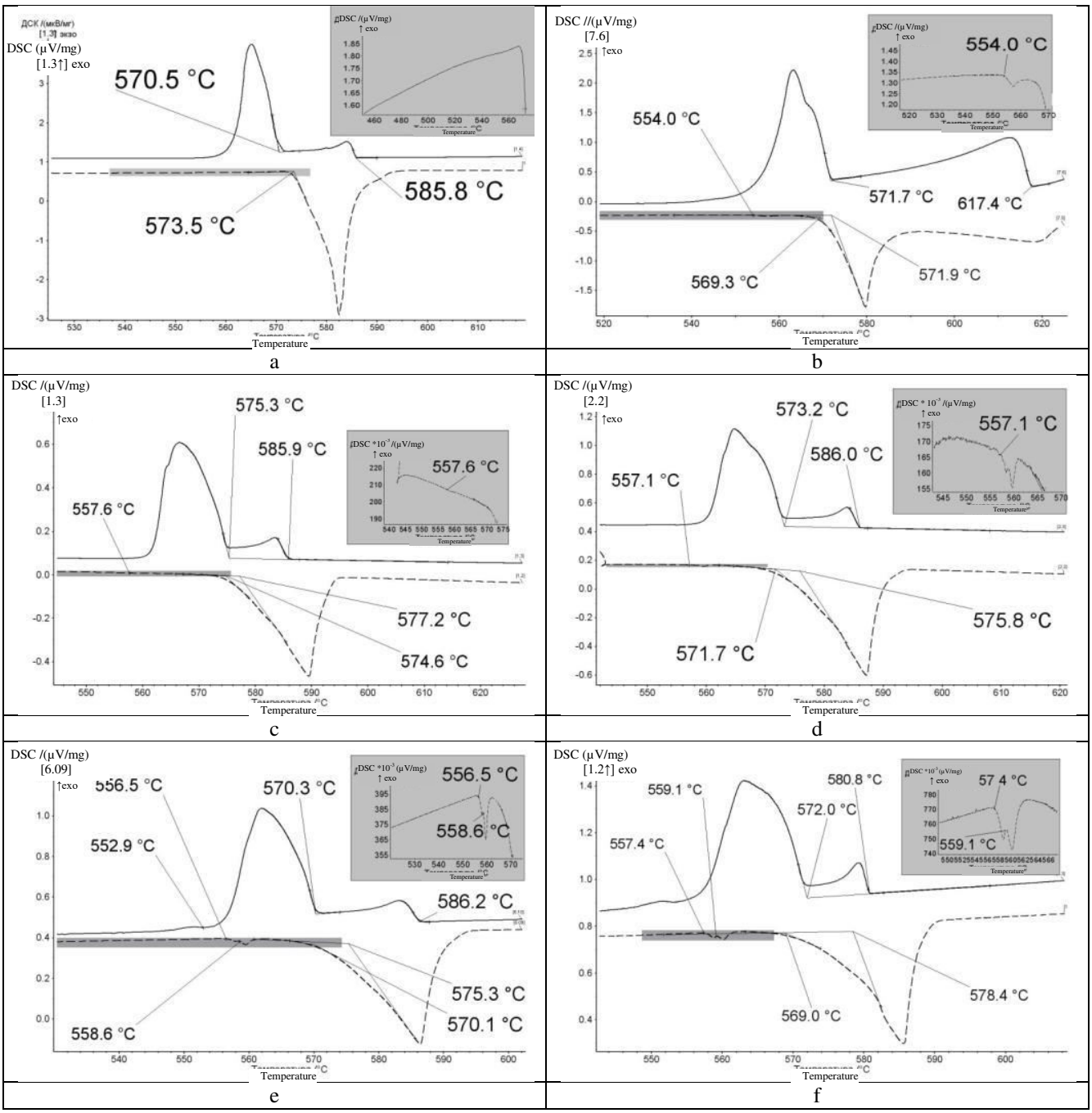


Figure-1. Heating and cooling thermograms of the alloys (cooling (continuous lines); heating (dashed lines)): a - AlSi11 alloy; b - AlSi7Mg0.3 alloy; c - alloy 1; d - alloy 2; e - alloy 3; f - alloy 4.

During heating, the thermal curve of the AlSi11 alloy shows a rather small thermal effect that is associated with the melting of the ternary eutectic and corresponds to the temperature of 554ºC (Figure-1b).

Of all the pilot alloys, alloy 1 with a Mg content of 0.13% has a least expressed maximum that shows the melting temperature of the ternary eutectic, which is explained by the small Mg_2Si phase in this alloy (Figure-1c). An increase in the Mg content of the pilot alloys leads to a corresponding increase in the thermal effect at the non-equilibrium solidus point.

Thus, the results of the thermal analysis allowed us to determine the liquidus, equilibrium and non-equilibrium solidus temperatures, as well as the crystallization interval of the alloys under study in both equilibrium and non-equilibrium conditions. This information is given in Table-3.

Table-3. Thermal analysis results.

Alloy	Liquidus, °C	Solidus, °C equilibrium/ non-equilibrium	Crystallization interval, °C in equilibrium/non-equilibrium conditions
AlSi11	586	574 / -	12 / -
AlSi7Mg0.3	617	569 / 554	48 / 63
1	586	575 / 557	11 / 29
2	586	576 / 557	10 / 29
3	586	575 / 557	11 / 29
4	581	569 / 557	12 / 24

The Mg content in the concentration interval under study does not affect the crystallization interval in non-equilibrium conditions. It should be noted that the crystallization interval of the pilot alloys is much narrower, more than twice compared to the AlSi7Mg0.3 alloy.

We further compared the casting properties of the new alloys to those of the standard ones and, consequently, determined their fluidity with using a spiral probe (Figure-2a). The averaged values are given in Figure-2b.

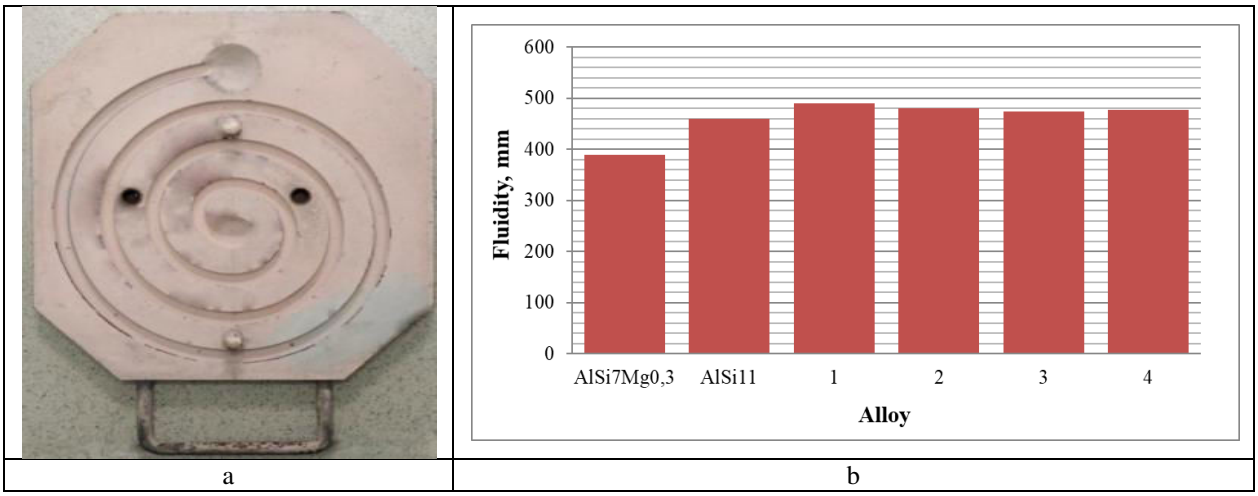


Figure-2. Determination of the fluidity of the alloys: a - mold for the spiral probe; b - measurement of the fluidity.

The new alloys have higher fluidity rates compared to the standard alloys. The fluidity of the pilot alloys is 23% more than that of the AlSi7Mg0.3 alloy, which is due to their smaller crystallization interval. When compared to the AlSi11 alloy, their fluidity is approximately at the same level.

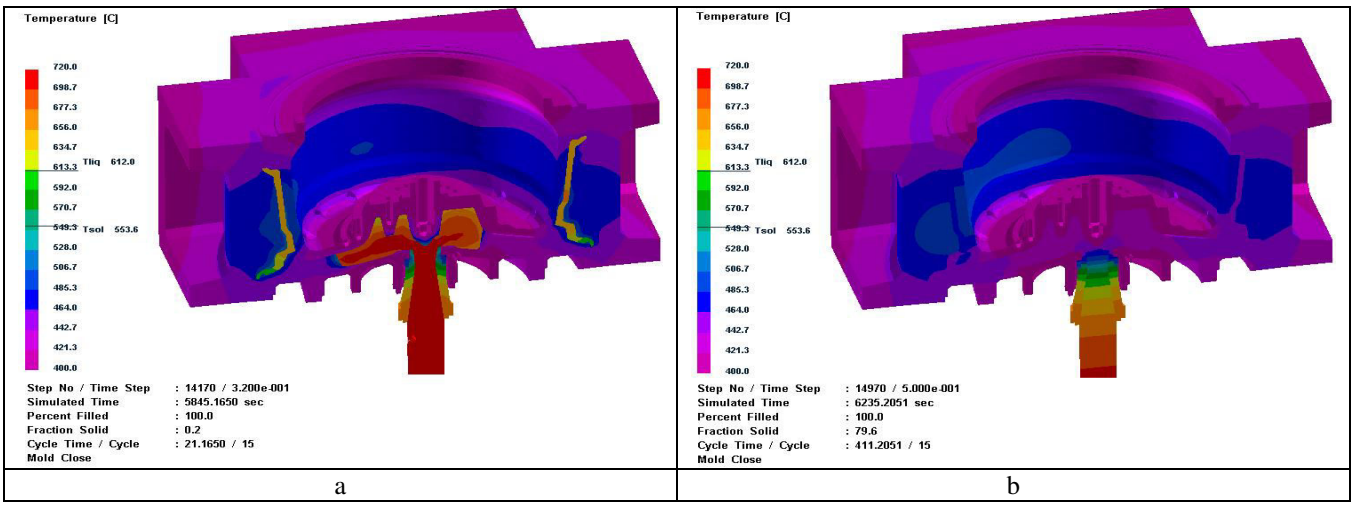
MODELING OF CASTING PROCESSES

Based on the data obtained, computer modeling in the ProCAST software package was carried out for the low-pressure casting of automotive wheels from the new alloys, namely the AlSi7Mg0.3 alloys under study; pilot alloys 1-4 and assessment of high-quality casting production potential based on the casting technology existing within SKAD. For modeling purposes, we selected an 18-inch wheel with a more noticeable difference in the casting properties of the alloys under study.

Using the ProCAST package, we studied the mold's cyclic operating temperatures, as well as the hardening process of castings, and revealed places with possible shrinkage defects.

Considering that the liquidus and solidus temperatures do not change depending on the Mg content (Table-3), there are no differences between the new alloys while modeling casting processes in the ProCAST package. Therefore, modeling was carried out for a new alloy 3 that was compared to the AlSi7Mg0.3 alloy.

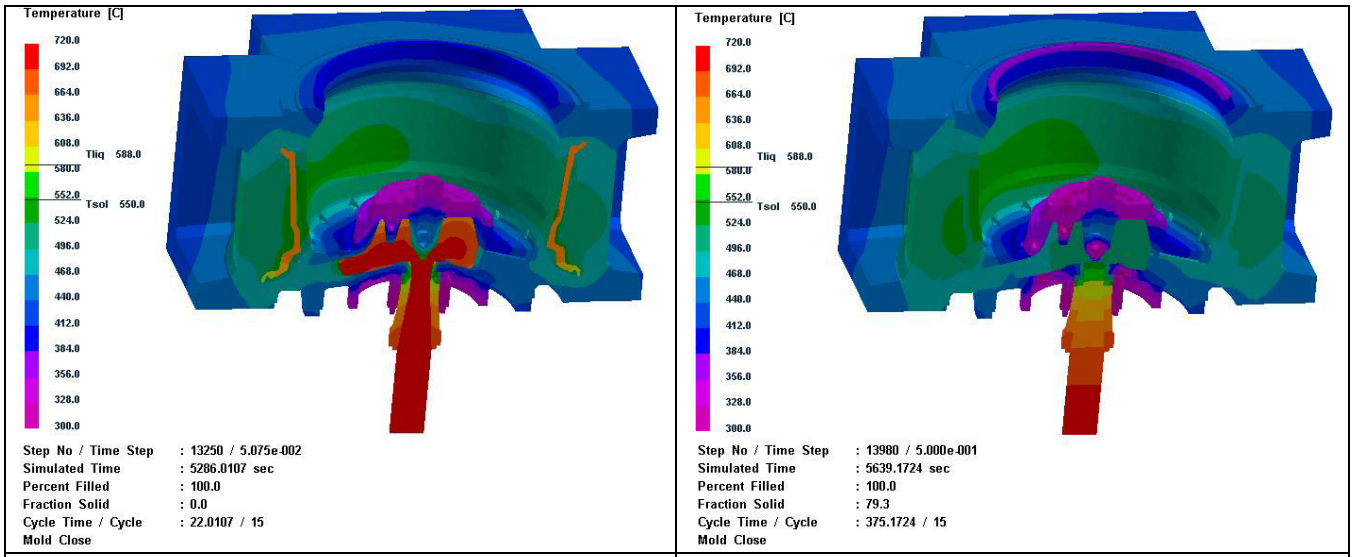
In the middle of filling, during the 15th casting cycle with the AlSi7Mg0.3 alloy, we obtained a maximum mold temperature of 530÷550°C at the point where the spoke and the rim are joined; the minimum temperature in the rim's top part was 420÷440°C. Full filling takes place at the 22nd second, and the duration of the whole 15th cycle is 411 seconds. The results of this thermal analysis are given in Figure-3.



a b

Figure-3. Temperature fields in the casting and mold when using the AlSi7Mg0.3 alloy: a - after 100% filling of the mold at the 15th cycle; b - at the end of the 15th cycle.

During filling, during the 15th casting cycle with a new alloy 3, the maximum mold temperature reached 545÷555°C at the point where the spoke and the rim are joined; the minimum temperature at the rim's top part was 495÷525°C. Full filling also takes place at the 22nd second, and the duration of the whole 15th cycle decreased to 375 s. The results of this thermal analysis are presented in Figure-4.



a b

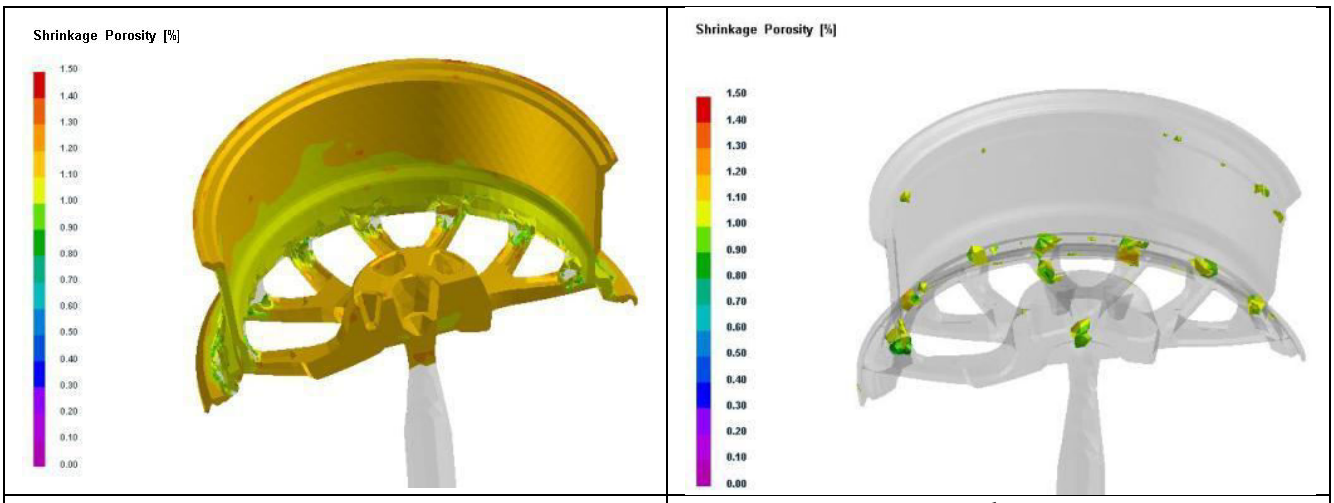
Figure-4. Temperature fields in the casting and form when using alloy 3: a - after 100% filling of the mold at the 15th cycle; b - at the end of the 15th cycle.

Analysis of the data presented in Figures 3 and 4 allows us to conclude that it takes less time for one cycle when making castings from the pilot alloy. The 15 casting cycles for 18-inch wheels from the new alloy 3 took 5286 seconds, while the casting process with the standard eutectic AlSi7Mg0.3 silumin lasted for 6235 seconds. This was due to the mold's high overheating at the 15th cycle when using the new alloy 3 [7].

One of the main drawbacks associated with the AlSi7Mg0.3 silumin and its wide crystallization interval is the formation of a high linear shrinkage factor, especially for large castings. All this leads to the formation of porosity and a sharp decrease in the mechanical properties of silumin-based castings [8]. Computer modeling helped us to study the formation of shrinkage defects in castings from the alloys under study. The results of these studies are presented in Figure-5.

Wheels cast from the hypoeutectic AlSi7Mg0.3 silumin (Figure-5a) show porosity along the whole section and practically in every casting area, which can cause terminal damage to wheels during operation. Besides, subsurface porosity will affect the product's decorative properties.

Wheels cast from the new alloy 3 (Figure-5b) are notable for concentrated porosity present only near the hump, heating unit and hub that is insignificant and non-critical for the finished products [9].



a b

Figure-5. Porosity in wheels cast from the alloys: a - AlSi7Mg0.3; b - new alloy 3.

Thus, analysis of modeling results of the low-pressure casting shows that castings from the new heat-hardenable alloy have higher quality parameters compared to those from the hypoeutectic AlSi7Mg0.3 silumin, which allows to increase industrial efficiency.

COMPARISON OF STRENGTH PROPERTIES

It is known that strength properties are largely affected by artificial aging after quenching, hold time [10] and aging temperature [11, 12], and also that too-high aging temperature can result in softening [13-16]. Therefore, this work does not include any studies related to determining optimum heat treatment parameters for the new alloy. The pilot wheels underwent the heat treatment line within factory temperature and time parameters; the aging temperature was 145°C and the hold time amounted to 370 minutes.

Analysis of the mechanical properties of the new alloys showed that alloy 3 with a Mg content of 0.25% has the best combination of strength and plastic properties. Next, we compared the mechanical properties of the wheels made from alloy 3 and AlSi7Mg0.3 that had undergone heat treatment for maximum strength.

To study mechanical properties, samples were cut out from the following wheel parts: 1) outer rim; 2) spoke; 3) hub. Figure-7 presents the mechanical properties of the alloys under study.

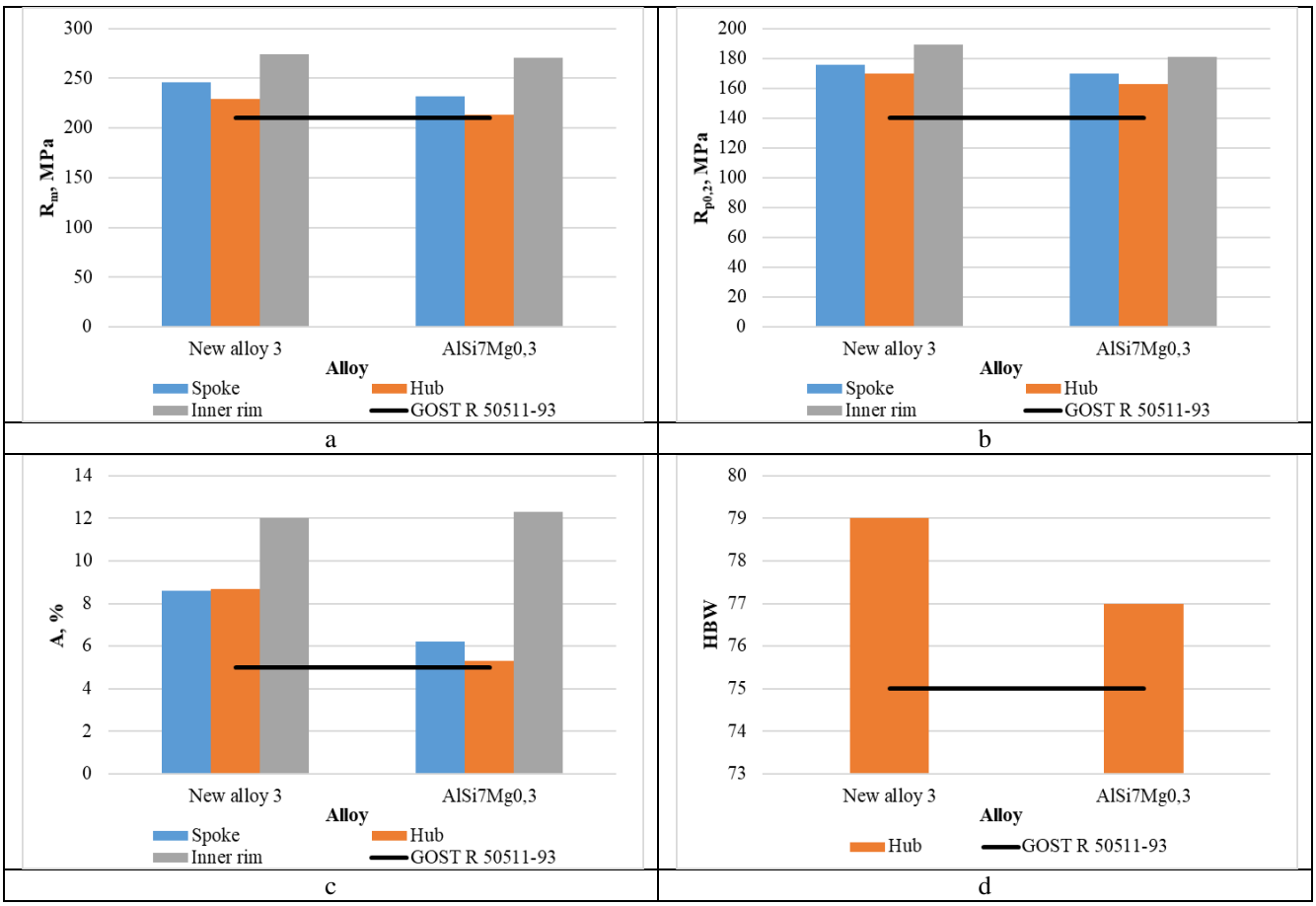


Figure-6. Comparison of the mechanical properties of wheels from the new alloy 3 and AlSi7Mg0.3: a - rupture strength; b - flow limit; c - relative elongation; d - hardness.

The most important indicator for automotive wheels is the results of bench tests that simulate loads acting on the wheel during car operation. Therefore, we conducted bench tests for one wheel model made from different alloys (3 and AlSi7Mg0.3).

At the same time, the wheels of this selected model must meet the following quality requirements:

a) Rotational bending test. The wheel must withstand not less than 200,000 cycles with a bending moment of 3, 851 N·m;

b) Impact test at the angle of 13°. The wheel must withstand an impact load of 558 kg.

The rotational bending tests were conducted under standard load until destruction, then the load was increased by 1,000 N·m in two stages. The impact tests were conducted with gradually-increasing loads until wheel destruction. The results of these bench tests are presented in Table-4.

Table-4. Bench test results.

Type of test	Load, N·m	Result, thousand cycles
New alloy 3		
Rotational bending	3,851	1,211
	4,851	636
	5,851	269
Impact at an angle of 13° and maximum load with positive result	1,000 kg	
Alloy AlSi7Mg0.3		
Rotational bending / 200,000 cycles with load of 3,050 N·m	3,851	974
	4,851	429
	5,851	258
Impact at an angle of 13° and maximum load with positive result	900 kg	

As shown in Table-4, in cases where the load increases by more than 1.5 times, wheels made from both alloys withstand more than 200,000 cycles, but those from new alloy 3 have a greater margin of strength.

CONCLUSIONS

The studies allowed us to obtain the following main results:

a) It was established that the ternary [α(Al)+Si+Mg_2Si] eutectic is formed in eutectic silumins as long as the Mg content increases.

b) The thermal analysis determined the crystallization interval of the new alloys in non-equilibrium conditions (29ºC), which turned out to be twice narrower than that of the well-known AlSi7Mg0.3 alloy (63ºC).

c) It is shown that at the same melt temperature, the fluidity of the new alloy is practically identical to that of the eutectic AlSi11 alloy, and is 23% higher than that of the hypoeutectic AlSi7Mg0.3 alloy.

d) Computer modeling of the low-pressure casting of automotive wheels from the alloys under study shows that wheels cast from the new alloy are notable for concentrated porosity present only near the hump, heating unit and hub and is non-critical for finished products, while in case of the AlSi7Mg0.3 alloy, there is shrinkage along the whole volume of castings, which can result in defects.

e) The strength properties of the new alloy exceed those of AlSi7Mg0.3 and meet all quality requirements.

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