Bulgarian Society for NDT
International Journal "NDT Days"
Volume III, Issue 5, Year 2020
ISSN: 2603-4018
eISSN: 2603-4646

Structural Features and Possibilities for Increasing the Operating Temperature of Aluminum Alloys

Roumen BATCHVAROV[1], Lenko STANEV[2], Serguei STANEV[2], Anna MANEVA[2], Mihail GEORGUIEV[2], Lilyana NENOVA[2]

[1]Société FRB (Fonderie Rapide Belfortaine), Groupe CITELE, France
e-mail: rb.frb@citele.fr

[2]Institute of Metal Science, Equipment and Technologies with Hydro- and Aerodynamics Centre "Acad. A. Balevski" at the Bulgarian Academy of Sciences, Sofia, Bulgaria
e-mails : stanev@ims.bas.bg; geo131@gmail.com; anna13@abv.bg; mgeorgiev@gmail.com; litali@abv.bg

Abstract
In the work, a technology for gravity casting of a cylinder head for an internal-combustion engine in a complex 3D printed sand mold is presented. The technology has been optimized with the help of virtual casting. The ability to improve the yield strength at increased operating temperature by alloying with Ni, in appropriate proportions, of industrially used alloys of Al-Si-Cu-Mg system has been shown.
It has been found that Ni alloying of these alloys leads, in the process of crystallization, to the extraction from the melt of Cu and Mg and their inclusion in intermetallic phases. As a result, the eutectic zone is partially or completely eliminated, which is a prerequisite for increasing the mechanical properties of these alloys, after homogenization and quenching at higher temperatures.

Keywords: virtual casting, head of gasoline engine, gravity casting into 3D printed sand molds

1. Introduction

Cylinder heads for automobile engines are aluminum castings, the design and production of which are constantly evolving and improving [1]. They are the main part of internal combustion engines (ICE), the part that closes the volume of the "combustion chamber", where the ignition and combustion of the fuel mixture, entered under high pressure, takes place. The cylinder head during fuel cycles in engines running at thousands of revolutions per minute is subjected to strong thermal and mechanical loads, regardless of the type of engine – diesel or gasoline.
The thermo-mechanical stresses in the cylinder head are greatest in the areas of the valve bridges, where the risk of cracking during long-term operation is a major problem [2]. The photo of Fig. 1 shows the location of the risk zone between the valves on the cylinder head.

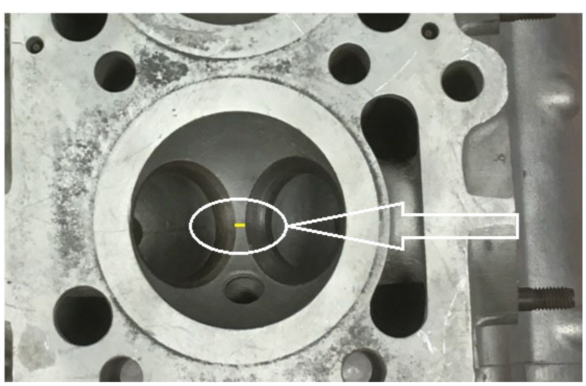


Fig.1.Picture of a part of motor head with indication of the critical area

The general tendency for reducing the number of cylinders (downsizing) of mass-produced cars, and in particular the transition to 3-cylinder engines, only amplifying the tendency to increasing specific power rating, which has been steadily increasing from the eighties onwards, for the gasoline and diesel engines [3.4]. This increases the temperature and operating pressure of the cylinder heads. In this way, operating temperatures can reach or exceed 250°C in the combustion chamber area.
In order for the cylinder heads to meet the new operating conditions (higher temperatures and pressures), manufacturers are obliged to increase the level of quality and in particular the limit of resistance to thermal fatigue. This can be achieved in different ways, the most important of which are the following:

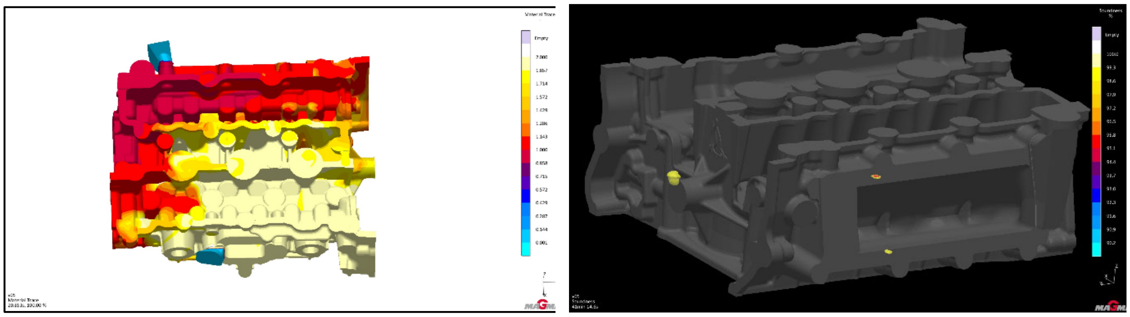
- by increasing quality (reduction of porosity and inclusions);
- by improving the structure (improving the microstructure and reducing the values of SDAS (Secondary Dendrite Arms Spacing);
- by selecting a suitable alloy, a suitable production process and heat treatment.

Aluminum alloys, mainly from the Al-Si-Mg group (AlSi7Mg0.3), are used for casting cylinder heads, but in recent years they more and more often are replaced by alloys of Al-Si-Cu group, which allow the engine to operate at higher operating temperatures (~ 250°C). Primary aluminum alloys AlSi7MgCu0.5, AlSi8Cu3, AlSi7Cu3MnMg, AlSi7MgCuFeNi, AlSi9Cu1Mg are used, with low nickel content and copper content in the range from 0.5% to 3%, with improved mechanical properties and stable temperatures at elevated temperatures are used [2,5,6,7,8,9,10].
The introduction of complex cooling circuits makes the geometry of the cylinder heads increasingly complex. The inner zones are formed by assembling 6 to 8 cores, including at least: heart of the oil cavity, heart of the suction channel with two valves, heart of the exhaust channel also with two valves, core of the pump, lower heart of the water chamber, upper heart of the water chamber. The geometric accuracy of this assembly is a major problem in the casting of cylinder heads.

2. Construction of 3D-printed sand mold for cylinder head casting and optimization of the technology by virtual casting

The object of research in the present work is the casting of a 3-cylinder head for a gasoline engine, whose accurate geometry is obtained by gravity casting in sand molds. The sand mold is made entirely of 3D-printed sand elements.
As the study progresses, it has been necessary to analyze different criteria for a choice of casting alloy, be compared several different aluminum alloys from the mentioned Al-Si-Cu group, knowing that the basic alloy is AlSi7Cu3Mg.
It has been used a method for casting of aluminum casing parts with a complex inner surface. The parameters for casting and feeding have been in advance optimized by virtual casting, according to the criterion for the best density.
Through the virtual optimization of the casting process, the number and the best location of the runners for entering (from two places) of the melt into the casting have been determined. The location of the feeder heads, the filling parameters, the heart temperatures, the shape and the casting have been also determined. The performed optimization is shown on Fig. 2.
On Fig. 2 (a) may be seen, shown in blue, the two points of the melt entrance. The metal passing through the one place is red, and through the other – light yellow, almost white. The color between light yellow and red correspond to a mixed melt from the two sources.
Fig. 2 (b) shows a view of the density-optimized casting. The places where the density corresponds to 2.67 g/cm³ are transparent, and where defects are predicted, the size of these

defects is colored according to the scale shown on the right. A total of 3 zones with presumed defects were observed, two with 95% and one with 90% of the ideal density.



a) b)

Fig. 2. Results of the made optimization

Several basic rules are followed in the construction process. Fig. 3a illustrates one of the rules – there must be at least three favorably placed marks on each core and the center of gravity of this core must be in the triangle described between the three marks. This rule has been followed. Another rule, however, has not been observed – a large and thin part is left outside the area of the three supports. This critical part of the core is shaded in yellow in Fig. 3b.

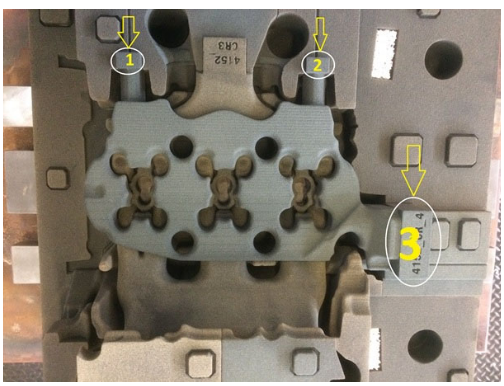


Fig. 3a. General view of the upper heart, placed in the mold with a numbering of the three marks

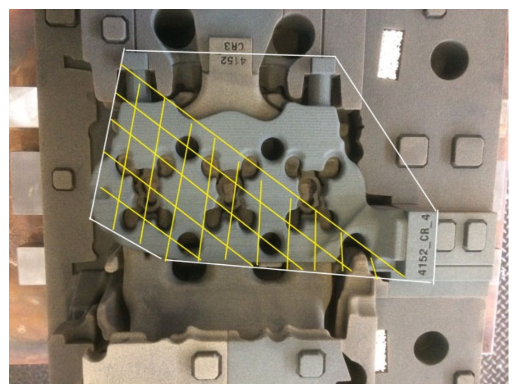


Fig. 3b. Shaded part from the upper core, left without support point

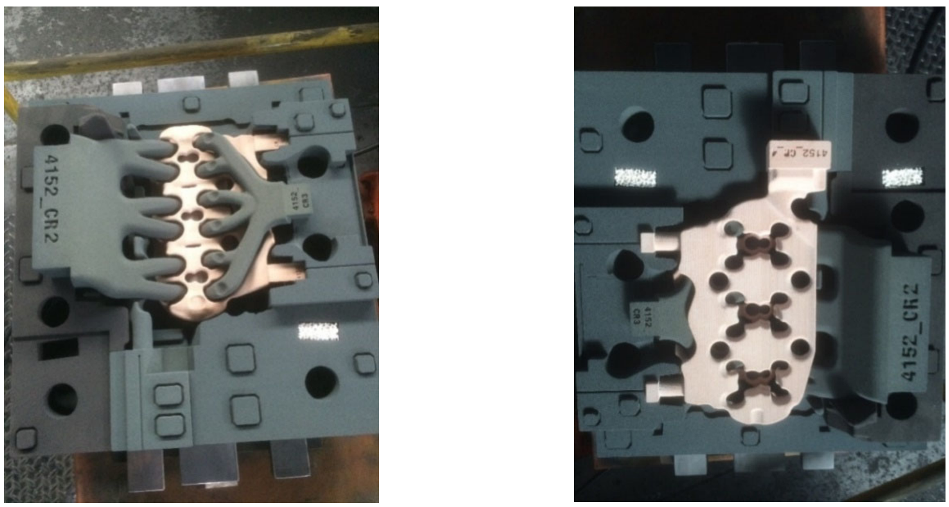
Upon a contact between the liquid metal and the core, mechanical stresses from the temperature differences occur. Additionally, due to the difference in density (the melt is denser than sand), the cores that are completely covered with metal tend to float up even during filling and also after the casting has solidified. The core heats up quickly, especially when it is fine and thin, the binder softens from the rise in temperature and tends to "slide" in the direction of the effort. The dimensional accuracy of this part, at such moments, cannot be guaranteed because a risk of deformation.

Where a mark necessary for the functional purpose of the channel formed by the casting core cannot be located, it is necessary to provide additional technical solutions to remove the obstacles, even if they prove to be more difficult or more expensive. In conventional technology, this problem is known and is solved by using metal fittings inside the core box, just before the core is made. In the case of 3D-printed segments, reinforcement is currently impossible.

One solution to avoid this risk of deformation is to use more durable materials. The cores forming the water cooling (upper and lower) are made and tested from two different 3D printed materials, called FDB-process and PDB-process. The main difference between these two processes is the binder. On Fig. 4 are shown photos of the two cores printed by a PDB process. The cores printed by the FDB process are already illustrated on Fig.3. Apart from the obvious difference in the color of the sand elements for each process, there is also a difference in the bending strength presented in Table 1.

Table 1. Bending strength at FDB and PDF process

Process	Bending strength
FDB (Furan Direct Binding)	>220 N/cm²
PDB (Phenol Direct Binding)	>250 – 500 N/cm²



a)core for lower cooling **б)core for upper cooling**

Fig.4. 3D-printed cores at PDB – process, placed in a mold for casting of a motor head

If the cores from both materials are deformed, there is another technical solution: fixing the hearts with the two types of cooling to each other in several places with aluminum brackets in a special shape. The installation of the brackets must be carried out after the installation of the cores for the suction and exhaust channels. Fig. 5 shows an example of the described fixation of the upper core in three points in order to counteract and avoid unwanted lifting of the core.
During the filling and crystallization, the aluminum brackets will support the upper core at the initially planned location. After a few minutes as the crystallization progresses, the aluminum casting becomes hard enough and the deformation of the core becomes more difficult.
It is known that the crystallization interval of the alloys from Al-Si-Cu-Mg group is more than 100°C and depends on the chemical composition of the main alloying elements, mainly silicon and copper [11].
It is also known [1,2,7,9] that the refined microstructure with SDAS ~ 20 µm has better fatigue crack resistance compared to the structure with SDAS ~ 50 µm. To avoid any possible defect causing cracking, the inner surfaces of the motor heads must be machined to a high smoothness (polished). It follows that the operating surfaces should have a tolerance for a machining and the future operating surface is located inside the casting, at best 2-3 mm from the surface in consideration.

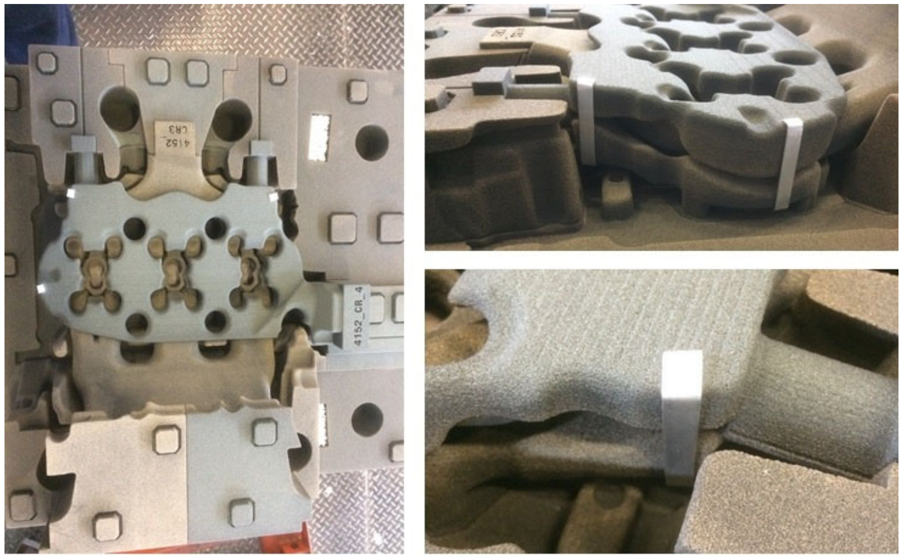


Fig. 5. Upper and lower core fixing with special aluminum brackets: left – top view; right – side view of the three brackets

Stack filling of the area near the cylinders is preferred to a filling from the bottom by flushing [12].

Taking into account these factors, simulation at the following initial parameters has been made: temperature of the melt Tm= 730°C; sand elements temperature – 21°C, temperature of metal coolers under the places for cylinders, before the beginning of the casting – 21°C, time for casting – 20 s, simultaneously through the two foreseen runners.

On the following Fig. 6 is shown the temperature field of the experimental casting, during crystallization, 2 minutes after the end of the filling. View from the bottom presents the temperature of the casting surface, close to the future operating surface of the combustion chambers of cylinders. The solidus temperature of the AlSi7Cu3Mg alloy is approximately 498°C.

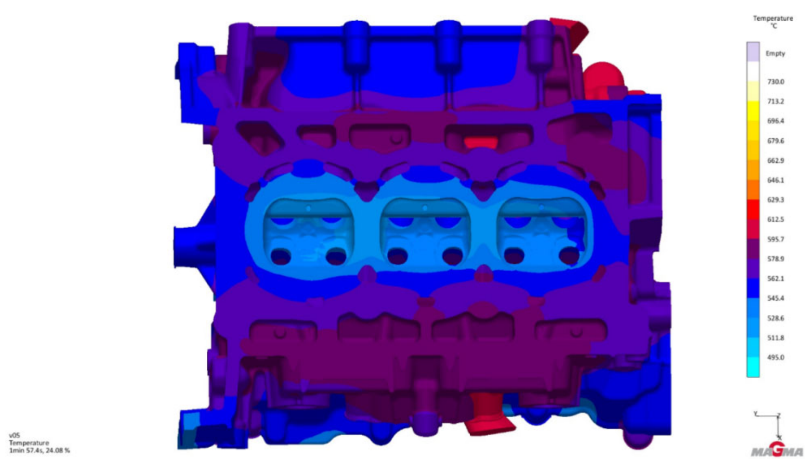


Fig. 6. Temperature of the lower part of the motor head casting, 120s after casting

Comparing the color of the casting in the area of the cylinders with the color scale, can be noted that partial solidification has begun, which is uniform for all three cylinder zones, but after 120 seconds there is no point or zone where the crystallization has ended. Even in the coldest zone, the temperature of about 30°C to complete the "liquidus – solidus" transition is not still reached. The duration of this transition has been extended for the following reasons:

- after 120 seconds the sand elements of the mould heat up considerably, as well as the metal coolers.
- feeder heads located above the feeding areas are still kept too hot and carry a lot of heat. This heat reduces the cooling gradient and further slows down temperature drop of the test surface.

3. Possibilities for influencing on the structure and properties of the alloys of Al-Si-Cu-Mg group by additional alloying with Ni

It is known that motor head castings are subjected to T6 heat treatment and it is believed that a higher homogenization temperature can increase the mechanical parameters. The question arises whether it is possible to achieve another phase equilibrium at a higher temperature of final solidification (solidus), which to improve the mechanical parameters at elevated temperatures (in the range of 250°C-300°C).

It is proved that for each alloy there is a correlation between the microstructural parameters (in particular SDAS) and the cooling time (or cooling rate).

Some guidelines in this direction is given by the results obtained in the study[11] of alloys of the Al-Si-Cu group, alloyed with nickel, where it was found that the presence of nickel in these alloys has a retarding effect on the kinetics of Al α-solid solution and Al-Si eutectic.

To study the possibilities for the influence of Ni on the structure and properties of alloys from the Al-Si-Cu-Mg system, 5 different alloys were studied.

AlSi7Cu3Mg alloy (EN AC-46300) was chosen as a first basic composition, in the second composition to the first composition nickel in the content of 0.6 ÷ 0.9% was added; in the third composition in addition to nickel (0.6 ÷ 0.9%) 0.1% zirconium was added. For comparison, two more alloys were studied: AlSi5Cu3Mg alloys (EN AC-45100) and one eutectic piston alloy AlSi12CuNiMg (EN AC-48000).

The study was conducted with the program "Thermo-Calc Software – Computational Materials Engineering". This is software that allows metallurgists by calculating the free enthalpy (Gibbs energy) to predict the various thermo-physical properties of metal alloys in equilibrium (phases present, liquidus and solidus temperature, etc.). This digital tool can be used to optimize alloys or develop new alloys, limiting the subsequent experiments and focusing only on elements that are likely to have a significant impact on the desired properties.

The thermodynamic calculation approach consists in minimizing the Gibbs energy in order to be characterized a system in equilibrium. To this purpose, Thermo-Calc uses the Calphad approach (computer connection of phase diagrams and thermo chemistry), which allows to take into account the interactions between chemical composition, temperature and pressure and to determine the phases present in many double and triple systems, then it is possible they to be extrapolated to complex systems [13].

The calculated results for three different temperatures 20°C, 250°C and 300°C are presented in three radar-type graphs (Figures 7, 8 and 9).

The use of radar graphics easily marks the significant differences between different groups of alloys. In the four sub-eutectic alloys, maximum amounts of the reinforcing double phase Al_2Cu are observed. In the case of the AlSi12CuNiMg alloy, the Al_2Cu phase is minimal. Instead, the complex quadruple phase Q dominates ($Al_5Cu_2Mg_8Si_6$, $Al_3Cu_2Mg_9Si_7$, and $Al_4Cu_2Mg_8Si_7$). As an be seen, this phase absorbs almost the entire amount of copper and nickel is present only in the aluminum-nickel (Al_3Ni) double phase.

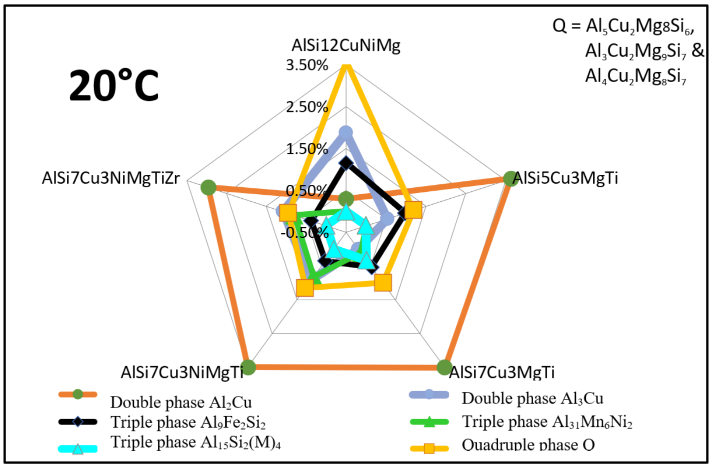


Fig. 7. Graphical representation of the content of six reinforcing intermetallic phases, present in the 5 investigated alloys at room temperature 20°C.

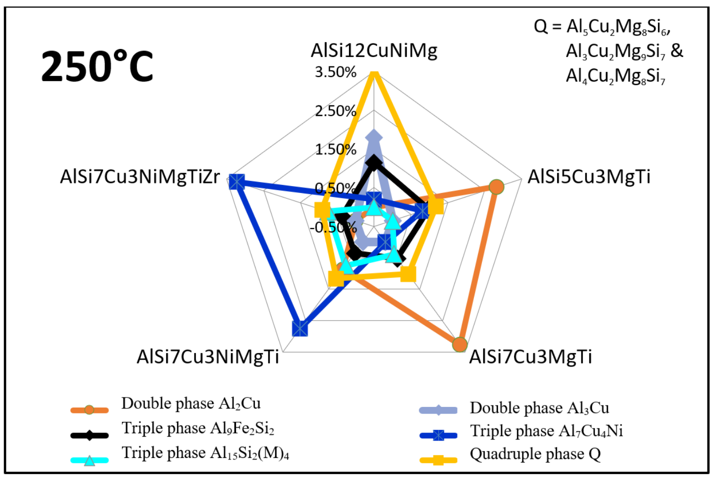


Fig. 8. Graphical representation of the content of six reinforcing intermetallic phases, present in the 5 investigated alloys at room temperature 250°C.

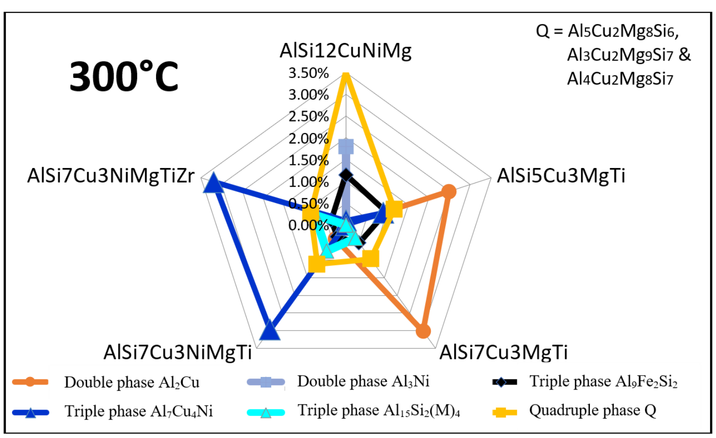


Fig. 9. Graphical representation of the content of six reinforcing intermetallic phases, present in the 5 investigated alloys at room temperature 300°C.

The precipitated phases presented in Fig. 8 and Fig. 9 are very similar in shape and quantity, which shows that at both temperatures, the strengthening is due to the same phases in all five alloys.

- For the eutectic alloy AlSi12CuNiMg these are the quadruple complex phase Q ($Al_5Cu_2Mg_8Si_6$, $Al_3Cu_2Mg_9Si_7$, $Al_4Cu_2Mg_8Si_7$), the double phase Al_3Ni, the triple phase $Al_9Fe_2Si_2$. These are exactly the same 3 phases, dominating at room temperature 20°C.
- For the two hypoeutectic alloys without nickel AlSi5Cu3MgTi and AlSi7Cu3MgTi, the same strengthening phases dominate as at room temperature – the double phase Al_2Cu, the quadruple phase Q ($Al_5Cu_2Mg_8Si_6$, $Al_3Cu_2Mg_9Si_7$, $Al_4Cu_2Mg_8Si_7$) and the triple phase $Al_9Fe_2Si_2$.The essential differences are that the small amount of nickel, instead of being in the Al_2Ni double phase, here is in the Al_7Cu_4Ni triple phase. Thus, in this alloy, although dominant, the quantity of the double phase Al_2Cu is 20-30% less than at room temperature.
- For the other two nickel-containing hypoeutectic alloys – AlSi7Cu3NiMgTi and AlSi7Cu3NiMgTiZr – significantly larger changes occur. The dual phase Al_2Cu is not presented or is weakly represented in a minimal quantity. Its first place is occupied by the triple phase Al_7Cu_4Ni, with almost the same dominant amount. On Fig. 8 and Fig. 9, this strengthening phase is shown in blue. The other two strengthening phases represented at 20°C – the quadruple complex phase Q ($Al_5Cu_2Mg_8Si_6$, $Al_3Cu_2Mg_9Si_7$, $Al_4Cu_2Mg_8Si_7$) and the triple phase $Al_9Fe_2Si_2$ are preserved at both elevated temperatures 250°C and 300°C.
- The results of Fig. 8 and Fig. 9 confirm that the presence of Ni in Al-Si-Cu-Mg alloys consumes a significant amount of Cu to form AlCuNi precipitations, instead of the Al_2Cu phase.
- The precipitations found in the AlSi7Cu3NiMgTi and AlSi7Cu3NiMgTiZr alloys at elevated temperatures of 250°C and 300°C are of the strengthening Al7Cu4Ni triple phase.

On the Fig. 10 are shown seven crystallization curves at slow cooling of four alloys from the considered Al-Si-Cu-Mg group (three of the curves are duplicated). Temperature measurements are performed sequentially: first measurement with AlSi7Cu0.5Mg alloy; immediately after the first measurement, up to 3% copper is added to the same alloy and 2 measurements are made; then 0.5% nickel is added and 2 new measurements are made; the last two measurements are made after the addition of another 0.5% nickel to reach 1% Ni.

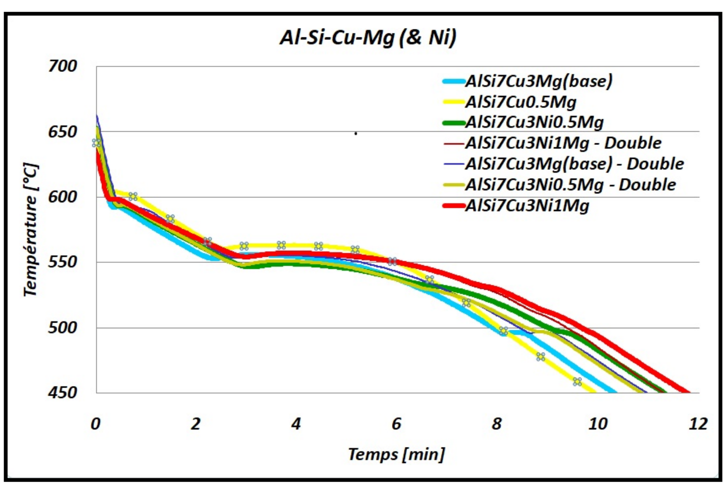


Fig. 10. Crystallization curves at slow cooling of four alloys from the Al-Si-Cu-Mg group

It can be seen that three of the curves do not have at 498°C a straight section – the AlSi7Cu0.5Mg alloy curve and the two curves for the AlSi7Cu3NiMgTi alloy. This suggests that there is no quadruple eutectic in the AlSi7Cu0.5Mg and AlSi7Cu3NiMgTi alloys, as in the first case there is not enough copper, and in the second case the copper is depleted with the formation of the triple intermetallic Al_7Cu_4Ni before the alloy cools to this temperature.

On Fig. 11 are shown the results of a yield strength study (Rp_{02}) at test temperatures of 20, 250 and 300°C for AlSi7Cu3Mg alloy, additionally alloyed with Ni and Zr. The results were compared with literature data [14, 15] for Rp_{02} of AlSi5Cu3 and AlSi12Cu4NiMg alloys in the T6 condition.

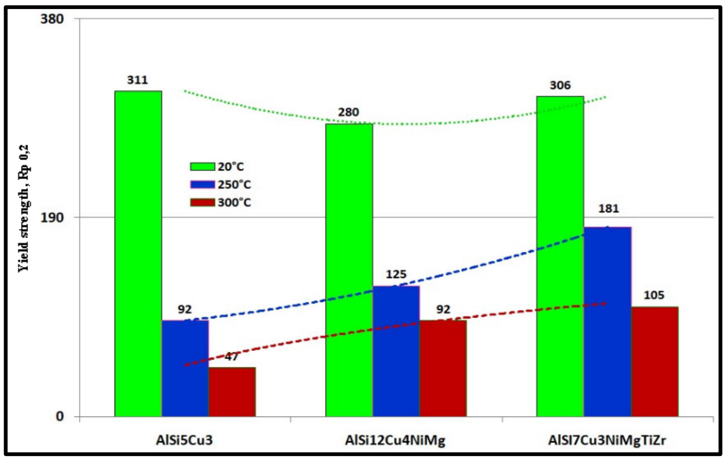


Fig.11. Comparison of the yield strength Rp02 [MPa] of AlSi5Cu3, AlSi12Cu4NiMg and AlSi7Cu3NiMgTiZr alloys at different test temperatures

It can be seen that at a temperature of 250°C and 300°C after alloying with Ni and Zr, the AlSi7Cu3Mg alloy has significantly higher values of the yield strength than the control alloys.

4. Conclusions

1. Technology for gravity casting in 3D printed mold of a cylinder head for a car engine is presented and optimized in design and technological terms.
2. Possibility to increase the operating temperature, by alloying with Ni, of the standardly used for casting of cylinder heads alloys from Al-Si-Cu-Mg system is considered.
3. Equilibrium crystallization curves of AlSi7Cu3Mg alloy, additionally alloyed with Ni, allow us to assume that in this alloy after 530°C, the quaternary eutectic cannot be formed, because the excess copper in the melt is already completely consumed by the peritectic reaction in the formation of the Al_7Cu_4Ni phase, which would lead to an increase in the solidus temperature.
4. It has been found that the addition of nickel to the alloys of Al-Si-Cu-Mg group, in controlled proportions with the copper content, forms suitable strengthening phases, stable at elevated operating temperatures in the range of 250°C -300°C.

References

1. Barlas, B., D.Ovono-Ovono, I.Guillot, G.Cailletaud. Ageing and Fatigue Behaviour in Cast Aluminium Alloys. Materials Science Forum, 2002, 396–402,1365–1370.https://doi.org/10.4028/www.scientific.net/msf.396-402.1365.
2. Angeloni M. Evaluation de la vie en fatigue en alliage d'aluminium A356 utilisé pour les culasses de moteurs. Thèse de Doctorat de l'école normale supérieure de Cachan, Université of São Paulo, São Carlos, 2011.
3. Bourassi N. PSA engines: "downsizing", a risky bet at the expense of premium (Moteurs PSA: "downsizing", un pari risqueau detriment du "premium"). https://www.latribune.fr/entreprises-finance/industrie/automobile/moteurs-psa-le-downsizing-un-pari-risque-au-detriment-du-premium-713793.html, 05/16/2017.
4. Sroka Z.J., M. Paropkari. Assessment ofthe engine boost modernized according to the rules of downsizing, Journal of Kones Powertrain and Transport, Vol. 22, №. 3, 2015.
5. Toschi S. Optimization of A354 Al-Si-Cu-Mg Alloy HeatTreatment: Effect on Microstructure, Hardnessand Tensile Properties of Peak Aged andOveraged Alloy, Metals, 8, 961, 2018.
6. doi:10.3390/met8110961 'www.mdpi.com/journal/metals' (pdf).
7. Ceschini, L.; A.Morri, S.Toschi, S.Johansson, S.Seifeddine. Effect of microstructure andoveraging on the tensile behavior at room and elevated temperature of C355-T6 cast aluminum alloy.Mater. Sci.83, 626–634, Des. 2015. [CrossRef]Effet de la microstructure etvieillissement excessif du comportement à la traction à température ambiante et à température élevée de l'alliage d'aluminium coulé C355-T6.
8. Ceschini, L.; A. Morri, S. Toschi, S. Johansson, S. Seifeddine. Microstructural and mechanical propertiescharacterization of heat treated and overaged cast A354 alloy with various SDAS at room and elevatedtemperature. Mater. Sci. Eng. A 648, 340–349. [CrossRef],2015.
9. Caceres C.H., M.B. Djurdjevic, T.J.Stockwell, Sokolowski J.H.. The effect of Cu content on the level of microporosity in Al-Si-Cu-Mg casting alloys. Scripta Metall. Mater.Sci., vol. 40 №5, pp 631–637, 1999.
10. Seifeddine S., E. Sjölander, T. Bogdanoff. On the Role of Copper and Cooling Rates on the Microstructure, Defect Formations and Mechanical Properties of Al-Si-Mg Alloys. Materials Sciences and Applications, 4, 171-178, 2013.
11. M. Krupiński, L.A. Dobrzański, J.H. Sokolowski. Microstructure analysis of the automotive Al-Si-Cu castings. Archives of foundry engineering Vol. 8, p.71-74, Issue 1/2008.
12. FR 3004730 (B1) – C22C, priorité:2013-04-19, Alliage de fonderue à base d'aluminium, SICTA.
13. Batchvarov R. Optimization of microstructuresby simulation with Magma-5. Colloquium of French users of Magma Soft, Nancy, France, 2014.
14. Stucky M. Alloy design by thermodynamic calculation with Thermo-Calc. https://metalblog.ctif.com/2018/07/23/lalloy-design-par-le-calcul-thermodynamique-avec-thermocalc/.
15. Les Alliages De Moulage, "Aluminium Pechiney" et "AEFIMET", pp. 6, 2001.
16. Yang Y.F. Precipitation Strengthening of Aluminum by Transition Metal Aluminides, Thesis submitted to the faculty of the Worcester Polytechinc Institute (Fr: Renforcement des précipitations de l'aluminium par les aluminiures de métaux de transition), April, 2012.