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Mold Temperature and Its Effect on Selected Properties of Cast AlSi5Cu2Mg Alloy

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Abstract

The European Commission's ambitious plan to reduce CO_2 emissions has a significant impact on the global automotive industry. Recent development of new diesel and petrol engines with direct injection is aimed at improving fuel efficiency while maintaining (or enhancing) engine performance. This naturally also increases the demands on the properties of the most stressed engine components (e.g., cylinder heads, engine blocks, pistons), which leads to the development of new materials. Presented work analysed the effect of different mold temperatures (60; 120; 180 °C) on mechanical, physical properties and microstructure of AlSi5Cu2Mg aluminium alloy. This alloy is currently being used for the production of cylinder head castings. The results showed that the changing mold temperature had an effect on mechanical properties (ultimate tensile strength and Young modulus values). SEM with EDX analysis of intermetallic phases revealed there were no size and morphology changes of Cu, Mg and Fe intermetallic phases when the mold temperature changed. No significant effect of different mold temperature on physical properties (thermal and electrical conductivity) and fracture mechanism occurred during experiment. Optimal combination of mechanical and physical properties of AlSi5Cu2Mg alloy was achieved using a permanent mold with temperature ranging from 120 to 180 °C.

Keywords: Mold, Temperature, AlSi5Cu2Mg, Cylinder head

1. Introduction

Direction of the automotive industry in recent years has been focused on the gradual transition to electromobility. Despite the e- mobility boom, the world is still not ready to get rid of cars with conventional combustion engines. Missing infrastructure (charging stations), battery recycling problems, lack of rare metals for battery production and currently a relatively high price of electric vehicles are key factors that are slowing down the switch to electromobility. For this reasons, automotive manufacturers are still focusing on the development of conventional petrol and diesel combustion engines. Recent development of these engines is taking place in an effort to improve fuel-efficiency while maintaining the engine performance. Demand on specific output, which describes the efficiency of an engine in terms of power-to-displacement ratio, is constantly increasing (Fig. 1). This is naturally leading to an increase in combustion temperature and pressure in internal combustion engines [1-4].

Of the many engine components, cylinder heads are the most complex castings located in passenger cars. They contain most of the mechanical components of an engine and determine the engine´s behaviour (cooling, torque, emissions, acoustics). Cylinder head castings production represents high demands on internal homogeneity, dimensional stability and accuracy, thermal conductivity, mechanical properties at ambient and elevated temperatures [5-7].

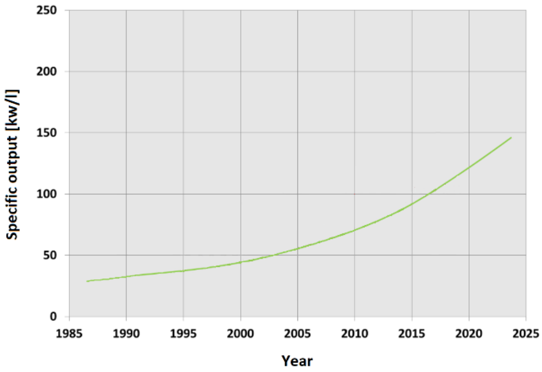


Fig. 1. Increasing demands on engine performance [5]

Among all cylinder head materials, aluminium alloys based on the Al-Si-Cu-Mg system are most commonly used for production of cylinder head castings. Al-Si-Cu-Mg alloys offer favourable combination of strength-to-weight ratio, good castability, high mechanical properties after heat treatment by age hardening due to the precipitation of Cu and Mg-rich strengthening phases and sufficient corrosion resistance [8,9].

2. Material and experimental methods

Hypoeutectic AlSi5Cu2Mg aluminium alloy in pre-modified state was used for experimental purposes. The alloy was supplied in non-grain refined state, as the alloy manufacturer limits the Ti content to max. 0.03 wt. % (standard content of Ti for sufficient grain refining effect of hypoeutectic aluminium alloys is ranging from 0.04 to 0.1 wt. % of Ti), i.e., it was not possible to use common grain refiners based on Ti (AlTi or AlTiB). Chemical composition of the experimental alloy is given in the Table 1. The batch with a total weight of 10 kg was melted in an electric resistant furnace. Casting temperature was set to 735 ± 5 °C. The melt was not degassed before casting. Measured average value of density index (DI) from 3 samples was 10.5 % (stand. deviation σ = 0,34). Prepared melt was poured by gravity casting into metal mold with 3 different temperatures (60; 120; 180 ± 15 °C). Cooling rate (Table 2.) was measured using thermocouple located in feeder area of the mold.

Experimental samples (tensile test bars with 8 mm diameter) for tensile test were prepared according to the ISO 6892-1 standard. Five tensile bars samples in as-cast state were made for each mold temperature (60; 120; 180 °C). Selected mold temperature range is not commonly used in practice (temperatures ranging from 200 to 350 °C are standardly used) and was chosen to ensure high cooling rate to obtain finer grain structure (due to the absence of grain refiners in the experimental alloy).

Microstructure of the experimental alloy was evaluated by TESCAN LMU II scanning electron microscope (SEM) with Bruker EDX analyzer. Samples for metallographic evaluation were prepared by coarse and fine wet grinding, polishing on an automatic polishing machine using a diamond emulsions (3 μm and 1 μm graininess) and etching with H_2SO_4 etchant.

Solidification path (process of crystallization) of the experimental alloy was evaluated by thermal analysis. Thermal analysis equipment included a K-type thermocouple located in the centre of cylindrical shaped metal mold. LabView 2 Hz software was used to record the measured values (temperature, time) during thermal analysis. Obtained data were used to generate cooling curve and its first derivative, by means of which the characteristic exclusion temperatures of experimental alloy´s structural components were determined.

Table 1.
Chemical composition of the experimental alloy

Alloy	Chemical composition [wt. %]		
	Si	Cu	Mg
	5.95	2.07	0.285
AlSi5Cu2Mg	Fe	Mn	Ti
	0.19	0.017	0.015
	Cr	Sr	Al
	0.016	0.009	Bal.

Table 2.
Cooling rate at different mold temperatures

Mold temperature [°C]	Coolig rate [°C/s]
60	4.2
120	2.0
180	1.8

The methodology for determination of thermal conductivity was based on the measurement of electrical conductivity using a Sigma Check 2 conductivity meter. Obtained values of electrical conductivity (σ) were used in the empirical formula (1) to calculate the thermal conductivity (λ).

$$\lambda = 4.29 \cdot \sigma - 13.321 \ [\mathrm{W \cdot m^{-1} \cdot K^{-1}}] \quad (1)$$

3. Results

3.1 Thermal analysis

Thermal analysis is one of the basic methods of liquid metal control. The solidification of each alloy is accompanied by the crystallization heat release, the amount of which depends on the elimination of the individual phases during solidification. Recorded data from the thermal analysis (temperature and time) are used to create a cooling curve for subsequent quantitative evaluation of the alloy´s solidification process. For a clearer description of the temperature points at which a certain structural component of the alloy crystallizes, a first derivative curve (dT/dt) is constructed [10,11]. Cooling curve of the experimental alloy and its first derivative are shown in Fig. 2. Exclusion temperatures, at which the exclusion of experimental alloy´s structural components began, are given in Table 3.

Solidification of the experimental aluminium alloy AlSi5Cu2Mg started at the liquidus temperature by nucleation of the α-phase dendritic network at 615 °C, followed by Al-Si eutectic precipitation at 546 °C and Al-Cu-Si eutectic at 522 °C. Exclusion of Cu and Mg rich intermetallic phase (most probably $Al_5Cu_2Mg_8Si_6$) occurred at 501 °C. The solidification process was completed at solidus temperature (479 °C).

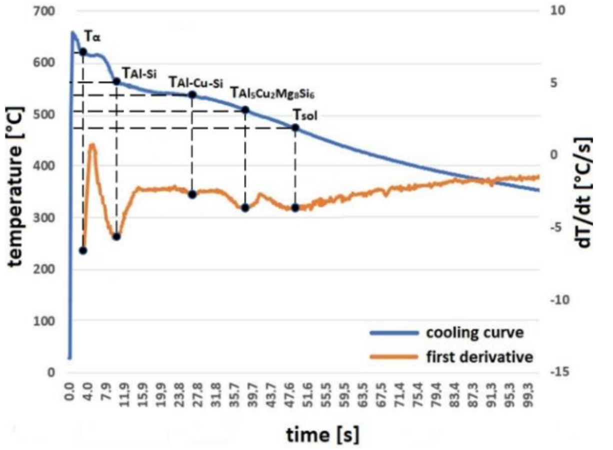


Fig. 2. Thermal and derivative analysis of the experimental alloy

Table 3.
Exclusion temperatures

Structural component	Temperature [°C]
α phase	615
Al-Si eutectic	546
Al-Cu-Si eutectic	522
$Al_5Cu_2Mg_8Si_6$	501

3.2 Mechanical properties

Average values (5 tested samples for each mold temperature) of the mechanical properties after tensile test are given in Table 4.

Table 4.
Mechanical properties of the experimental alloy (as-cast state)

Mold temperature [°C]	UTS [MPa]	YS [MPa]	A_5 [%]	E [GPa]
60	182	121	2	70
120	199	122	2	76
180	200	123	2	74

The lowest values of ultimate tensile strength (UTS) were reached for samples casted into the mold with 60 °C. An approx. 9 % increase in UTS and Young modulus (E) values was recorded when the mold temperature has risen from 60 to 120 °C. Subsequent increase in mold temperature from 120 to 180 °C had no significant effect on UTS and E values. As it is shown in Table 4., values of Yield strength (YS) were ranging from 121 to 123 MPa. It can be concluded that different mold temperatures did not significantly affect YS of tested samples.

Ductility is one of the most important mechanical characteristics of cylinder head castings. During operation, the cylinder heads are exposed to changing conditions (cold engine start, gradual heating, maximum load, cooling) and must be able to operate in a wide range of temperatures (from - 40 °C at engine start in northern regions to about 200 °C at maximum load in subtropical parts of the world). Satisfactory ductility values are therefore key to ensuring trouble-free operation of the cylinder heads during their life cycle, regardless of climatic conditions. As it is shown in Table 4., all experimental samples reached the ductility value of 2 %, regardless of the mold temperature. Compared to the ductility values of aluminum alloys that are most often used for the production of cylinder heads (Table 5.), the experimental alloy AlSi5Cu2Mg reached together with the alloy AlSi7Mg0.3 significantly higher ductility values among the selected alloys in as-cast state produced by gravity metal mold casting.

Table 5.
Ductility values of selected alloys (as-cast state)

Alloy	A_5 [%]
AlSi6Cu4	1
AlSi9Cu1Mg	1
AlSi7Cu3Mg	1
AlSi8Cu3	1
AlSi7Mg0,3	5

3.3 Physical properties

One of the most important physical characteristics of engine parts components is thermal conductivity. Sufficient thermal conductivity of aluminium alloy castings intended for production of thermally loaded engine components (e.g. cylinder heads) is key to ensure optimal engine operating temperature at various conditions [11].

Thermal and electrical conductivity values depending on different mold temperature are given in the Table 6. The measured data listed in the Table 6. showed that different mold temperatures had only negligible effect on values of thermal and electrical conductivity during experiment.

Table 6.
Thermal and electrical conductivity values (as-cast state)

Mold temperature [°C]	Electrical conductivity [% IACS]	Thermal conductivity [$W·m^{-1}·K^{-1}$]
60	35.6	140
120	36.1	142
180	36.4	143

The most commonly used aluminium alloys in the production of cylinder heads (Table 7.) are reaching the thermal conductivity values in the range from 110 to 180 $W·m^{-1}·K^{-1}$. The experimental alloy AlSi5Cu2Mg with thermal conductivity from 140 to 143 $W·m^{-1}·K^{-1}$ is thus included (together with the alloy AlSi9Cu1Mg and AlSi7Mg0.3) among the alloys with the highest thermal conductivity produced by gravity casting into permanent molds.

Table 7.
Thermal conductivity of selected alloys (as-cast state)

Alloy	Thermal conductivity [$W·m^{-1}·K^{-1}$]
AlSi5Cu3	120 - 130
AlSi9Cu1Mg	130 - 150
AlSi7Cu3Mg	110 - 120
AlSi8Cu3	110 - 130
AlSi7Mg0,3	160 - 180

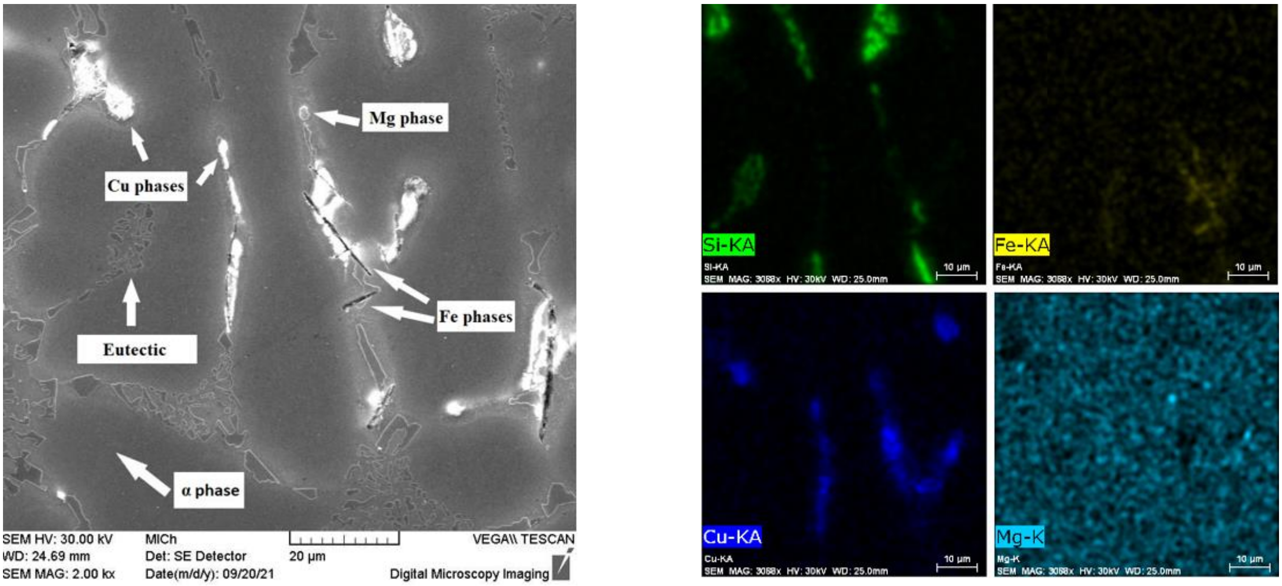


Fig. 3. Microstructure of the experimental alloy (left) with EDX chemical elements mapping (right)

3.4 Microstructure

Microstructure of the experimental alloy (Fig. 3) consisted of α phase, eutectic and Cu, Mg, Fe-based intermetallic phases.

Intermetallic phases β-Al_5FeSi with needle morphology (Fig. 4) were excluded near to the Cu-based intermetallic phases and phases with increased Mg content (Fig. 3) were observed in the form of isolated oval particles. Different mold temperatures had no noticeable effect on the size and morphology of the individual intermetallic phases.

Cu-rich intermetallic phases were observed as oval-shaped isolated particles (Fig. 5a) or as ternary eutectic in big compact morphology containing smaller oval particles (Fig. 5b).

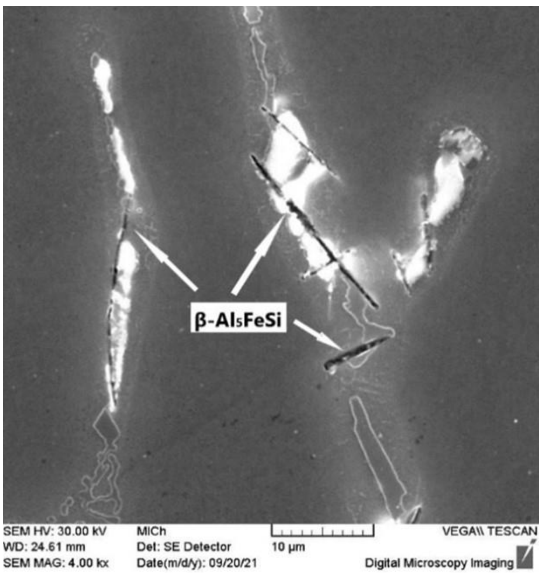
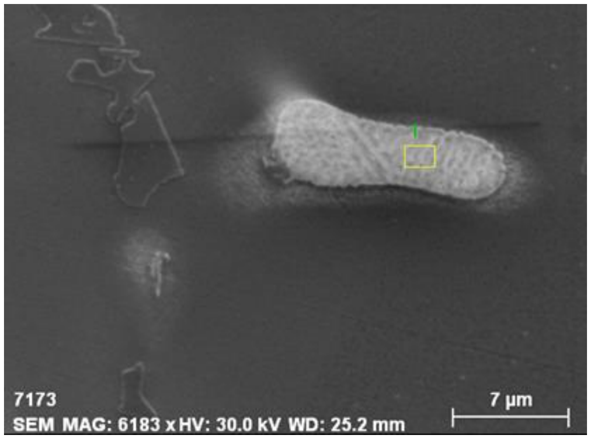


Fig. 4. Needle morphology of Fe intermetallic phases (SEM)



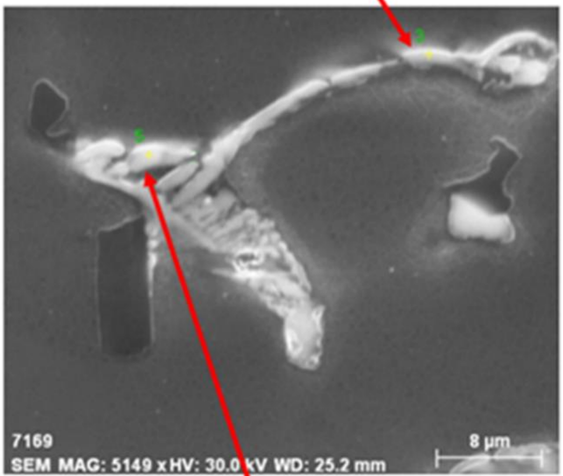
Spectrum: 1

El	AN	Series	unn. C [wt. %]	norm. C [wt. %]	Atom. C [at. %]	Error	(1 Sigma) [wt. %]
Al	13	K-series	84.22	77.86	87.00		4.25
Si	14	K-series	4.50	4.16	4.47		0.25
Cu	29	K-series	19.45	17.98	8.53		0.53
		Total:	108.18	100.00	100.00		

Fig. 5a. Morphology of Cu intermetallic phases (SEM) with EDX analysis

Spectrum: 3

El	AN	Series	unn. C [wt. %]	norm. C [wt. %]	Atom. C [at. %]	Error (1 Sigma) [wt. %]
Al	13	K-series	108.07	82.71	91.85	5.45
Cu	29	K-series	22.59	17.29	8.15	0.61
		Total:	130.66	100.00	100.00	



Spectrum: 5

El	AN	Series	unn. C [wt. %]	norm. C [wt. %]	Atom. C [at. %]	Error (1 Sigma) [wt. %]
Mg	12	K-series	2.80	2.65	3.44	0.20
Al	13	K-series	72.63	68.89	80.36	3.67
Si	14	K-series	3.56	3.37	3.78	0.21
Cu	29	K-series	26.44	25.08	12.42	0.70
		Total:	105.43	100.00	100.00	

Fig. 5b. Morphology of Cu intermetallic phases (SEM) with EDX analysis

3.5 Fracture surface

Samples for evaluation of the fracture surfaces were taken from the torn tensile test bars. One sample with best combination of mechanical properties for each mold temperature (60; 120; 180 °C) was selected for fracture surface evaluation. Fracture surfaces of tested samples depending on the mold temperature are shown in Fig. 6.

Al-Si-based alloys consisting of a highly plastic matrix of α-Al solid solution, within the crystals of eutectic Si together with intermetallic phases are precipitated. These structural components achieve significantly higher hardness values but very low plastic properties. The resulting appearance of the fracture surface thus depends on the failure mechanism of the matrix together with the morphology and size of the eutectic Si and intermetallic phases [12].

Evaluating the experimental samples, the transcrystalline ductile fracture mechanism is applied in the case of matrix fracture. Fracture of α-phase dendrites was characterized by the formation of plastically reshaped ridges. The experimental alloy was modified, i.e. eutectic Si occurred in the form of small plates rods

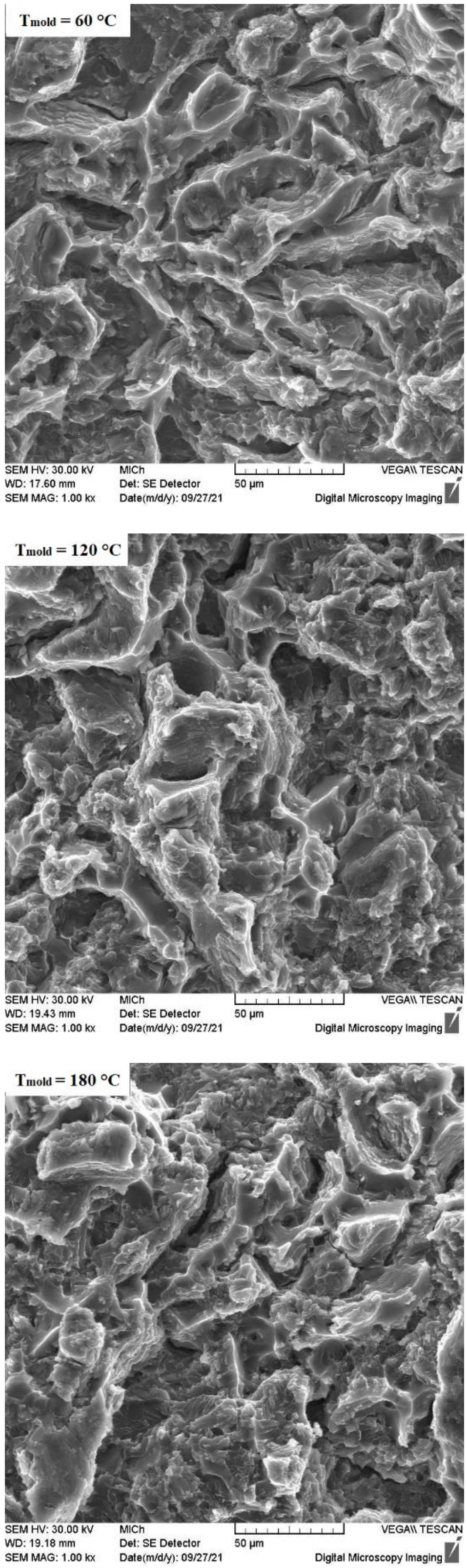


Fig. 6. Fracture surfaces of experimental alloy

or fibers. The presence of eutectic Si in the modified state reflected on the fracture surfaces by the occurrence of dimple morphology with locally occurring facets of smaller dimensions. Because the fracture surface morphology of the test specimens did not differ significantly, it can be stated that different mold temperatures did not affect the fracture mechanism of the experimental samples. Due to the presence of modified Si in the experimental alloy, the fracture surfaces were characterized by a high proportion of ductile fracture without significant occurrence of large facets, which are characteristic in unmodified alloys, in the structure of which eutectic Si occurs in the form of large plate-like structures. Thus, a high proportion of ductile fracture could have a favorable effect, in particular on the ductility and fatigue characteristics of the alloy.

4. Conclusions

The main aim of this work was to analyse the impact of mold temperature on selected properties of AlSi5Cu2Mg aluminium alloy intended for the production of cylinder head castings. The purpose was to select optimal mold temperature to secure best combination of mechanical and physical properties of experimental alloy for our future experiments. The following conclusions were drawn from the obtained data:

- Changing the mold temperature from 60 to 120 °C caused increase in UTS and E values. Subsequent increase in mold temperature from 120 to 180 °C did not significantly impact UTS and E values.
- Ductility of the experimental samples (A_5 = 2 %) was not affected by changing mold temperature. The most commonly used aluminum alloys for the production of cylinder heads achieve the ductility in the range of 1 to 5 %. The ductility of the experimental alloy was in the upper range of these values.
- Different mold temperatures had only a negligible effect on thermal and electrical conductivity and YS values. With the achieved thermal conductivity in the range of 140 to 143 $W \cdot m^{-1} \cdot K^{-1}$, the experimental alloy AlSi5Cu2Mg, together with the alloys AlSi9Cu1Mg and AlSi7Mg0.3, ranks among the most commonly used cylinder head aluminum alloys with the highest thermal conductivity.
- No size and morphology changes of Cu, Mg and Fe intermetallic phases with changing mold temperature occurred.
- There was no visible change in fracture mechanism depending on the mold temperature.
- Best combination of mechanical and physical properties of the experimental alloy was achieved by gravity casting into a metal mold with temperature ranging from 120 to 180 °C.

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