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SECTION 6. Metallurgy and energy.

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METAL MOLD CASTING OF CAST IRON AND ALUMINIUM PISTONS

Abstract*: The results of computer simulation of metal mold casting of cast iron and aluminium pistons for an automobile are presented in the article. Analysis of casting flaws into the pistons materials obtained at the different conditions of casting: values changing of melts flows, adding of the second vent, adding of a feeding point, a metal mold tilt and changing of the casting orientation into the mold was performed. Rapid cooling of aluminium melt leads to incomplete filling of the metal mold channels without additional elements of a gating system. Complete filling of the mold and the lowest deformation of material after cooling are ensured by changing of the aluminium casting orientation into the mold (by 180 degrees). Casting of the cast iron pistons is recommended to perform by adding of the second vent and the feeding point, as well as when the metal mold tilt by 90 degrees.*

Key words*: a piston, a metal mold, grey cast iron, aluminium alloy, melt, shrinkage.*

Language*: English*

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Introduction

Special requirements apply to manufacturing of automobile pistons. The pistons are exposed to significant temperature and mechanical loads, wear due to increased friction [1]. Implementation of these requirements is ensured by rational choice of material and manufacturing accuracy of the automobile piston. The aluminium pistons have sufficient strength, high heat resistance and low weight. The cast iron and steel pistons are used less frequently. Dimensional accuracy and low roughness of contact surfaces of the automobile piston are achieved after machining of a workpiece. The workpiece for the automobile piston is obtained by different methods (casting and forging). Gravity casting into the special casting mold (the metal mold [2]) is one of the methods to obtain the workpiece for the piston. So as materials for the metal mold have high heat conduction then melts when pouring are cooled rapidly. This can lead to incomplete filling into the castings. This casting flaw into the thin-walled castings (for example, into the automobile pistons) is particularly pronounced. Aluminium alloys after cooling have shrinkage to a greater extent (in 2 – 3 times) than shrinkage of gray cast irons [3 – 6]. Thus, for probability decreasing of casting flaws formation it is necessary to choose the optimal casting modes and rational configuration of the mold by performing analysis of metal mold casting of the cast iron and aluminium pistons for the automobile. Experiments were carried out by means of finite element modeling into a special computer program for reducing time of simulation and obtaining of the reliable results.

Materials and methods

Simulation of metal mold casting of the cast iron pistons (gray cast iron EN-GJL-300 [7]) and the aluminium pistons (aluminium alloy A356 [8]) for the automobile was carried out into the special computer program LVMFlow.

A three-dimensional casting model of the automobile piston and the gating system for computer simulation of metal mold casting is proposed in the Fig. 1. The solid models were cavities into the metal mold. The first solid model includes: the cavity for filling and subsequent cooling of melts, the cavity of a slit gate for melt supply into the mold cavity, the cavity of a vent for gases withdraw from the mold cavity and control of filling it by melt, the cavity of a downsprue for melt supply from a pouring basin to other elements of the gating system, the cavity of the pouring basin for pouring of melt.

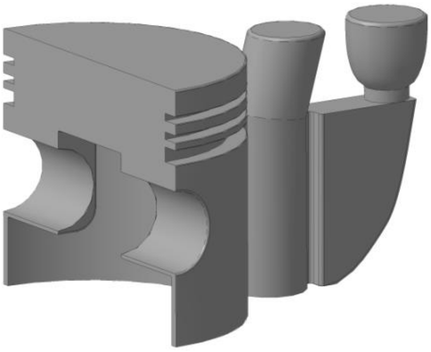


Figure 1 – The three-dimensional casting model of the automobile piston and the gating system in the cross section.

The casting process of the automobile pistons under the different modes and configurations of the mold was researched:

1. Values changing of melt flow of gray cast iron EN-GJL-300 (1st mode – 0.397 kg/s; 2nd mode – 0.893 kg/s and 3rd mode – 1.396 kg/s) and aluminium alloy A356 (1st mode – 0.136 kg/s; 2nd mode – 0.305 kg/s and 3rd mode – 0.477 kg/s).
2. Adding of the feeding point.
3. The metal mold tilt with the casting by 90 degrees.
4. Adding of the second vent.
5. Changing of the casting orientation into the metal mold by 180 degrees.

Chemical compositions of gray cast iron EN-GJL-300 and aluminium alloy A356 in percentage are presented in the tables 1 and 2.

Table 1

Chemical composition of gray cast iron EN-GJL-300 in percentage.

Fe	C	Si	Mn	P	S
93.84	3.1	2.1	0.8	0.08	0.08

Table 2

Chemical composition of aluminium alloy A356 in percentage.

Al	Si	Mg	Mn	Cu	Fe	Zn	Ti
91.387	7.5	0.45	0.1	0.2	0.15	0.2	0.013

Initial temperature of melt of grey cast iron was taken by 1290 °C, initial temperature of melt of aluminium alloy was taken by 710 °C.

Liquidus temperature for gray cast iron EN-GJL-300 is 1196.791 °C, for aluminium alloy A356 is 617.848 °C.

Solidus temperature (eutectic) for gray cast iron is 1152.048 °C, for aluminium alloy is 566.418 °C.

Changes of physical, mechanical and other properties of the casting materials (gray cast iron EN-GJL-300 and aluminium alloy A356) from temperature changing are presented in the Fig. 2 – 7.

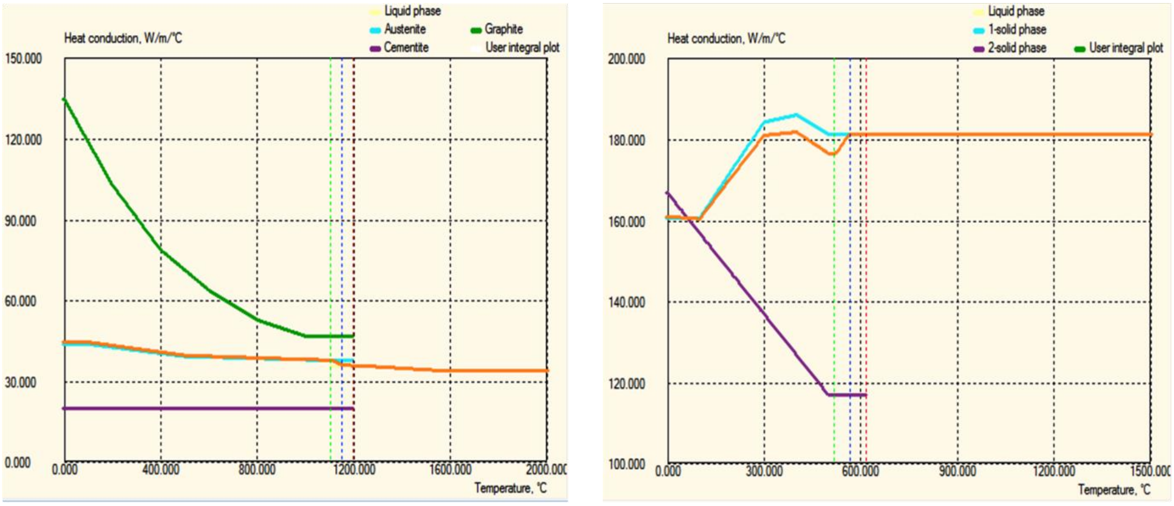
Gray cast iron EN-GJL-300 at cooling can be in the following phases: liquid phase, austenite, cementite and graphite. Aluminium alloy A356 at cooling can be in the following phases: liquid phase, 1-solid and 2-solid phases. Significant increasing of heat conduction is observed in graphite phase of gray cast iron EN-GJL-300 at cooling. Aluminium alloy A356 has higher heat conduction in cooled condition than gray cast iron EN-GJL-300. It is noted that in the first solid phase of aluminium alloy heat conduction decreases, and in the second solid phase heat conduction increases. Gray cast iron in graphite phase has high specific heat at beginning of cooling. Specific heat of the cast iron casting is reduced in 3 times at complete cooling. Specific heat of aluminium alloy in both the first and the second solid phases decreases in the range 190 – 200 J/(kg × °C). Specific heat is 980 J/(kg × °C) at complete cooling of aluminium alloy (in the first solid phase). Density of gray cast iron EN-GJL-300 in austenitic and cementite phases is about 3 times more than density of aluminium alloy A356 in all phases. However, density of gray cast iron in graphite phase is less than density of aluminium alloy in all considered phases.

Gray cast iron EN-GJL-300 has lower viscosity than aluminium alloy A356 in liquid phase. This allows to reduce time of melt filling of gray cast iron into the mold. Grey cast iron has higher mechanical properties in solid condition. Values of Young's modulus, bulk modulus and shear modulus don't change at cooling of aluminium alloy. Poisson's ratio for grey cast iron EN-GJL-300 is 0.26, for aluminium alloy A356 is 0.33. Yield stress of gray cast iron is more than aluminium alloy. Yield stress of gray cast iron increases uniformly on the range of cooling temperature. Yield stress of aluminium alloy increases very rapidly on the small range of cooling temperature.

Modified constitution diagrams [9] of gray cast iron EN-GJL-300 and aluminium alloy A356 at cooling are presented in the Fig. 8. The temperature ranges of formation of different phases in gray cast iron EN-GJL-300 and in aluminium alloy A356 are presented on the modified constitution diagrams. Percentage of the second chemical element in alloys is indicated by the red dotted line.

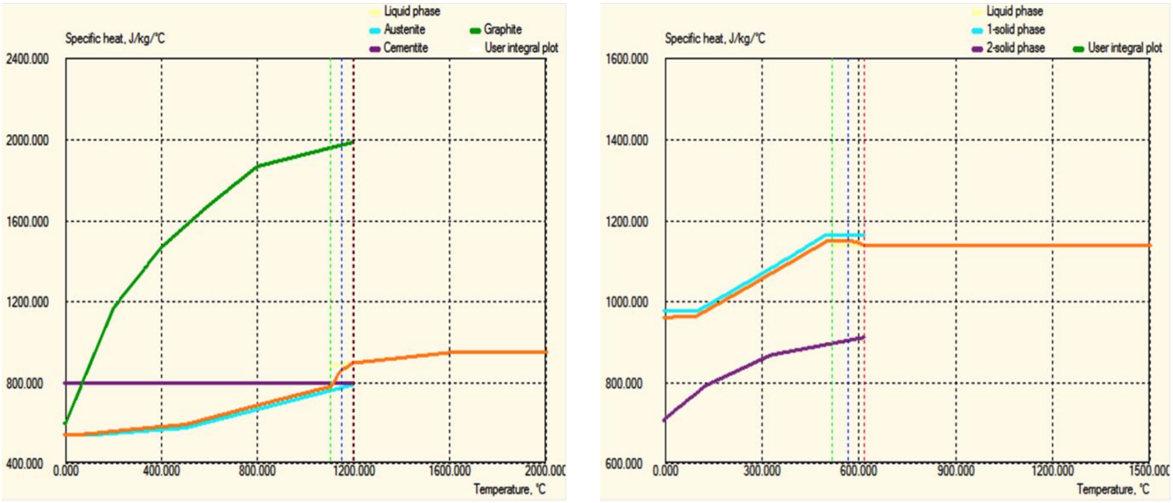
CLF up of gray cast iron EN-GJL-300 in 1.7 times more than aluminium alloy A356 (50% vs. 30%). CLF down for accepted melts is same (30%).

Total emissivity of gray cast iron EN-GJL-300 in liquid and cementite phases is 0.1, in austenitic phase is 0.11, in graphite phase is 0.53. Total emissivity of aluminium alloy A356 in liquid and the second solid phases is 0.1, in the first solid phase is 0.7.



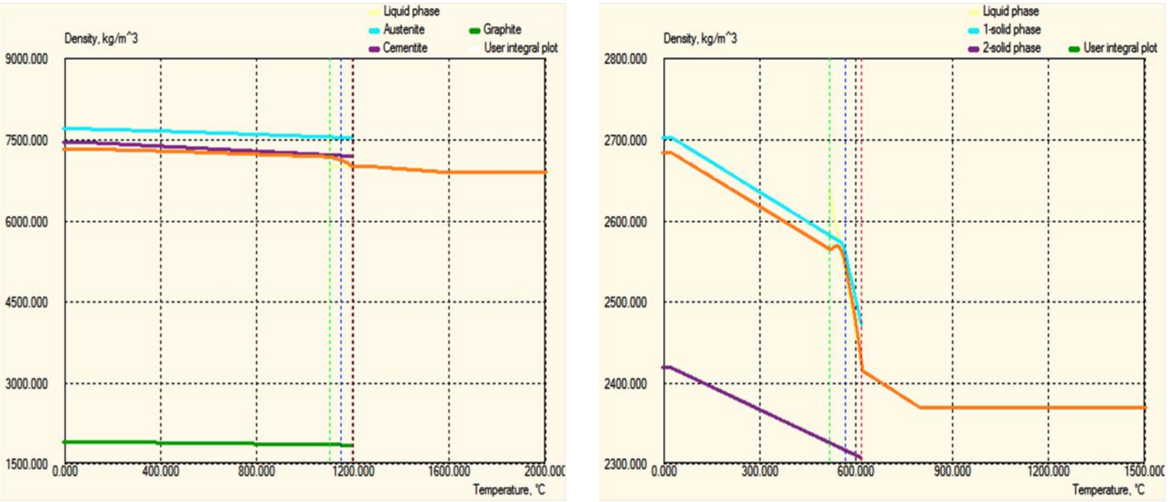
A B

Figure 2 – The dependencies of heat conduction of grey cast iron EN-GJL-300 (A) and aluminium alloy A356 (B) from materials temperature.



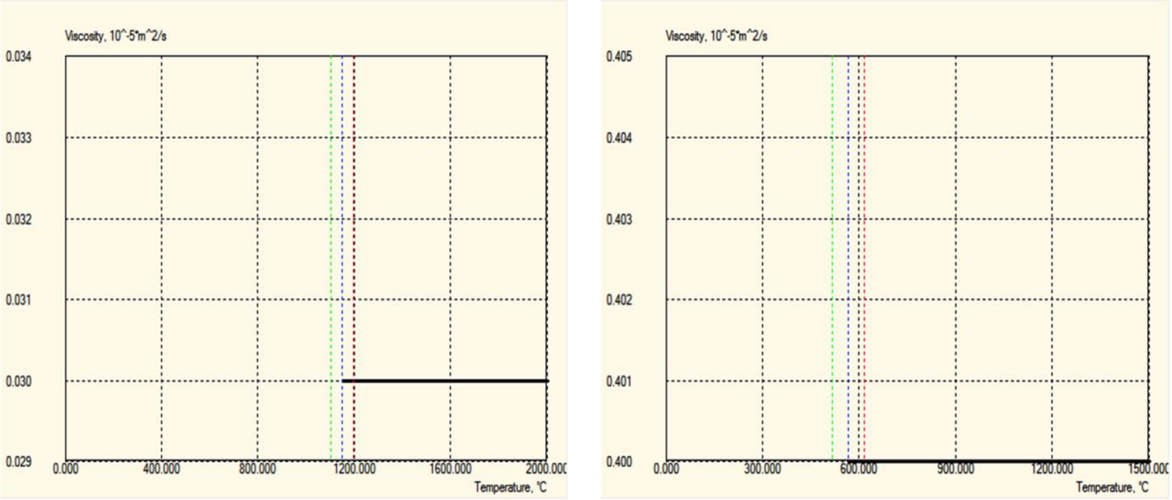
A B

Figure 3 – The dependencies of specific heat of grey cast iron EN-GJL-300 (A) and aluminium alloy A356 (B) from materials temperature.



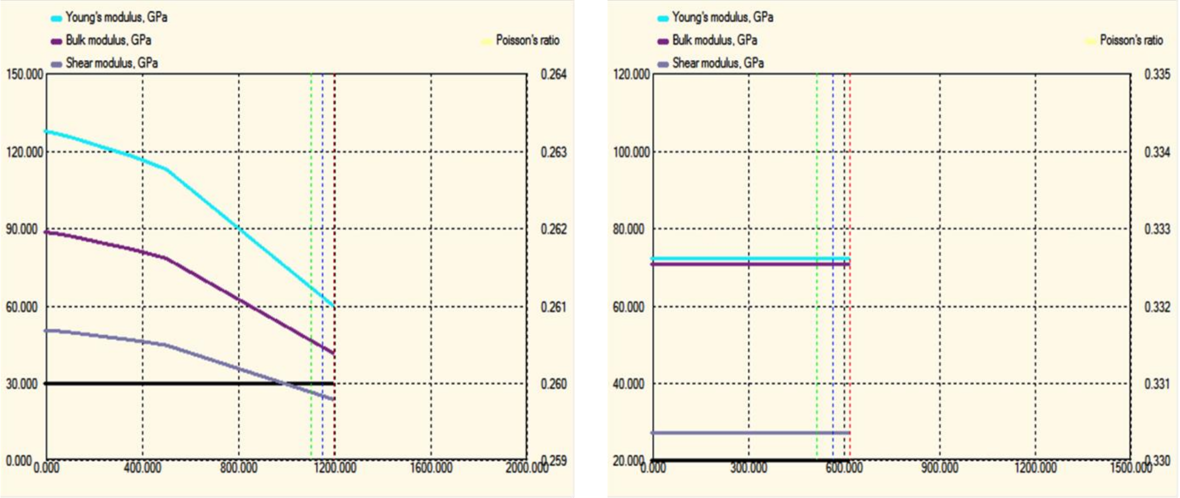
A **B**

Figure 4 – The dependencies of density of grey cast iron EN-GJL-300 (A) and aluminium alloy A356 (B) from materials temperature.



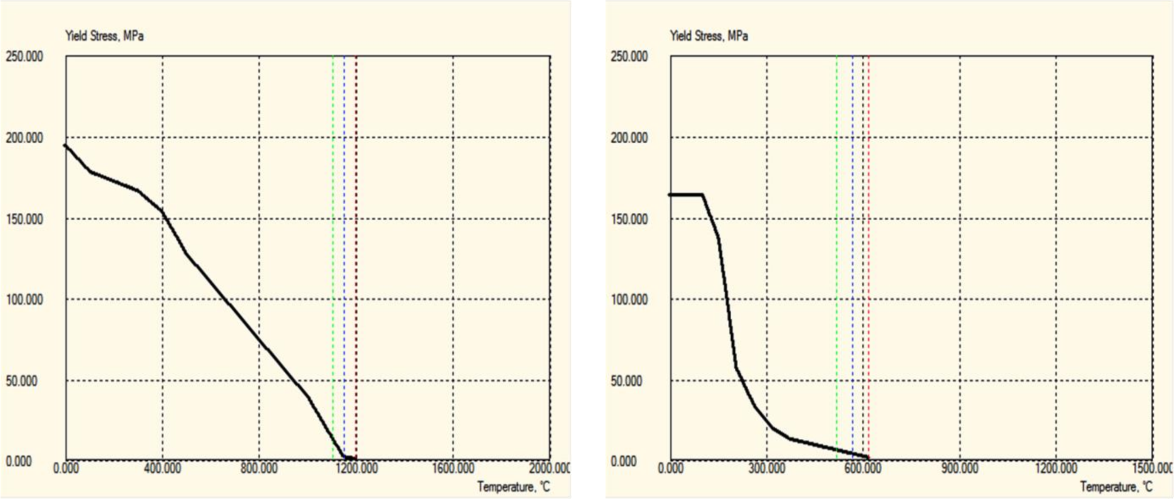
A **B**

Figure 5 – The dependencies of viscosity of grey cast iron EN-GJL-300 (A) and aluminium alloy A356 (B) from materials temperature.



A **B**

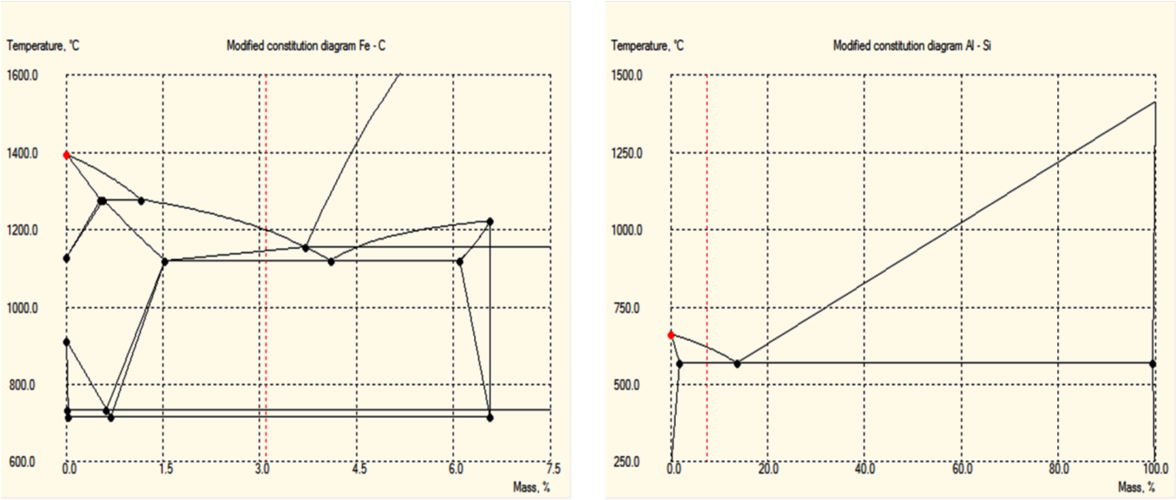
Figure 6 – The dependencies of Young's modulus, bulk modulus, shear modulus and Poisson's ratio of grey cast iron EN-GJL-300 (A) and aluminium alloy A356 (B) from materials temperature.



A

B

Figure 7 – The dependencies of yield stress of grey cast iron EN-GJL-300 (A) and aluminium alloy A356 (B) from materials temperature.



A

B

Figure 8 – The modified constitution diagrams of grey cast iron EN-GJL-300 (A) and aluminium alloy A356 (B).

The range of grains growth rates in melt of gray cast iron EN-GJL-300 is 0.001-0.2 (mm × s)/°C, in melt of aluminium alloy A356 is 0.1-0.5 (mm × s)/°C. The ratios range of nucleation to grain growth rate in melt of gray cast iron is 0.0001-0.001, in melt of aluminium alloy is 0.01-0.1.

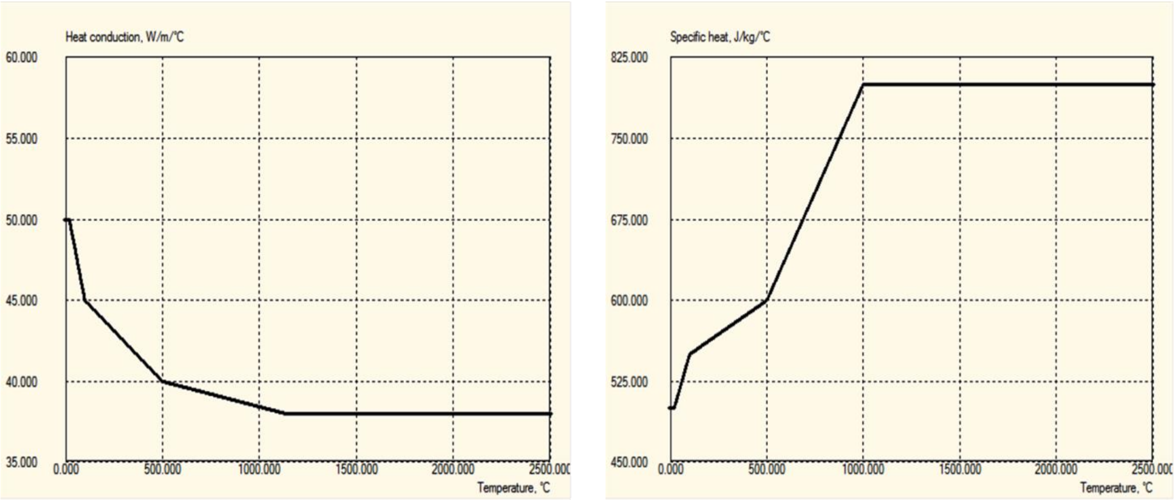
Changes of physical properties of material of the metal mold (gray cast iron) from temperature changing are presented in the Fig. 9.

Heat conduction of the mold increases, and specific heat decreases when cooling of the castings. Values of considered physical properties don't change at high temperatures of the metal mold. Values of heat conduction and specific heat of the metal mold correspond to values of heat conduction and specific heat of gray cast iron EN-GJL-300 in austenitic phase.

The metal mold was heated to temperature of 200 °C at casting of the pistons. Total emissivity of the metal mold is taken by 0.93, gas-permeability is taken by 1.53 × 10^{-6} m^2/Pa × s and rigidity is taken by 1.

Changes of physical properties of channels environment of the metal mold from temperature changing are presented in the Fig. 10.

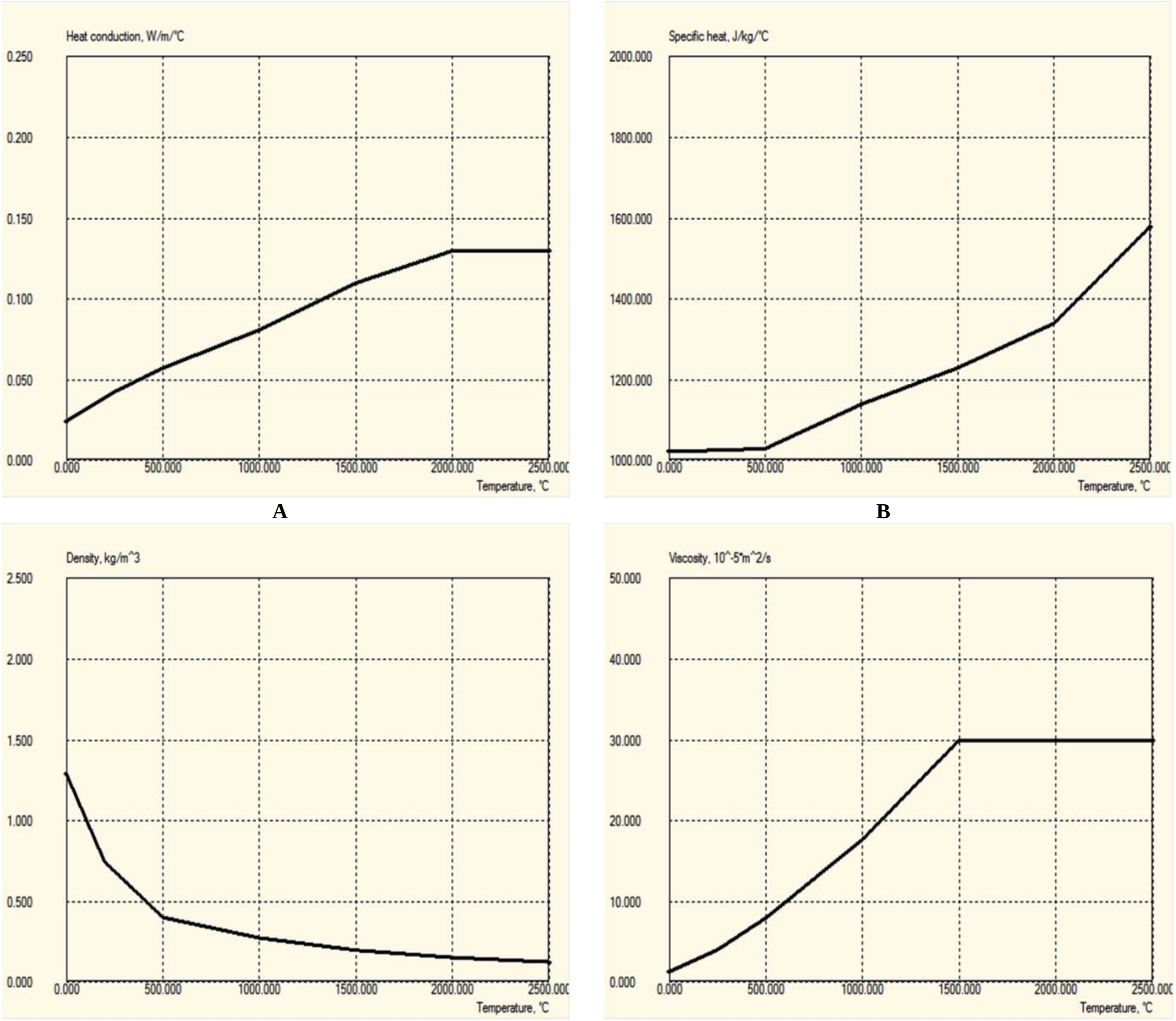
Heat conduction, specific heat and viscosity of air increase, and density reduces when filling of the metal mold by melt of gray cast iron and aluminium.



A

B

Figure 9 – The dependencies of heat conduction (A) and specific heat (B) of the metal mold (grey cast iron) from temperature.



A

B

C

D

Figure 10 – The dependencies of heat conduction (A), specific heat (B), density (C) and viscosity (D) of channels environment (air) of the metal mold from temperature changing.

Initial temperature of air into the metal mold channels was taken by 20 °C. Dimensions of the metal mold were taken by 193.8 × 102.6 × 87.4 mm for reducing of the calculation time of the casting process. Dimension of a cell for all models was taken by 3.8 mm. Boundary conditions for all planes of the metal mold were taken by normal. Heat transfer was carried out through surfaces. The calculation was performed by the quasi-equilibrium model taking into account convection. Segregation wasn't taken into account. Solution of the systems of the linear equations was performed by the Gauss-Seidel method [10]. Initial gas pressure outside and inside of the metal mold was taken by 1 Bar. Friction factor of melts flow of grey cast iron and aluminium was taken by 0.9. Melts are poured from a ladle (the angle of melt pouring into the pouring basin is 30 degrees).

Results and discussion

The results of computer simulation of metal mold casting are presented as cooled the three-dimensional castings models of the automobile pistons.

The pistons castings of the automobile made of grey cast iron EN-GJL-300 after casting with different flows of melt are presented in the Fig. 11.

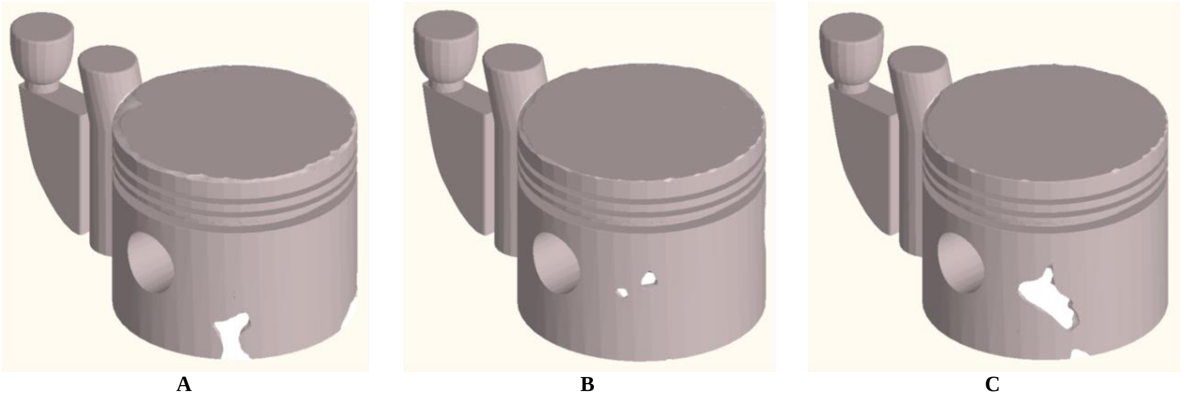

A B C

Figure 11 – The castings configurations of the automobile pistons (grey cast iron EN-GJL-300) after cooling: A – melt flow of 0.397 kg/s (1st mode); B – melt flow of 0.893 kg/s (2nd mode); C – melt flow of 1.396 kg/s (3rd mode).

The pistons castings of the automobile after cooling have incomplete fillings in the field of a skirt and a head. Herewith, maximum incomplete filling is observed into the piston after casting with melt flow of 1.396 kg/s. Filling time of the metal mold by melt and cooling time was: 30.15 s for the first mode, 30.444 s for the second mode and 30.291 s for the third mode. Volume shrinkage of gray cast iron EN-GJL-300 after casting in the second and the third modes is formed to a greater extent than in the first mode (0.13% vs. 0.12%). The cavities of the metal mold were filled on 98.2 – 98.3% after cooling of melt.

The pistons castings of the automobile made of aluminium alloy A356 after casting with different flows of melt are presented in the Fig. 12.

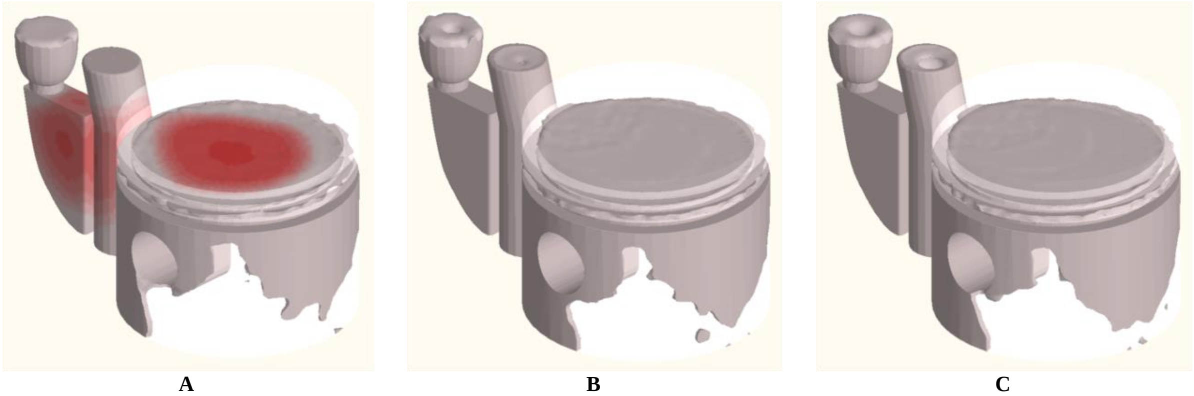

A B C

Figure 12 – The castings configurations of the automobile pistons (aluminium alloy A356) after cooling: A – melt flow of 0.136 kg/s (1st mode); B – melt flow of 0.305 kg/s (2nd mode); C – melt flow of 0.477 kg/s (3rd mode).

Incomplete filling is about 38% after casting of the aluminium pistons. Time casting of the pistons was amounted to 26.7 s. Filling of the metal mold is performed on 59.9% at melt flow of aluminium of 0.136 kg/s. Volume shrinkage of material was amounted to 0.46% after premature shutdown of the calculation of the casting process by the program. Volume shrinkage of material at the second casting mode is 1.09%, at the third casting mode is 1.39%.

The pistons castings of the automobile made of grey cast iron EN-GJL-300 and aluminium alloy A356 after casting with same flow of melts are presented in the Fig. 13. This technology provides additional supply of melt to the mold cavity in comparison with the previous modes of metal mold casting.

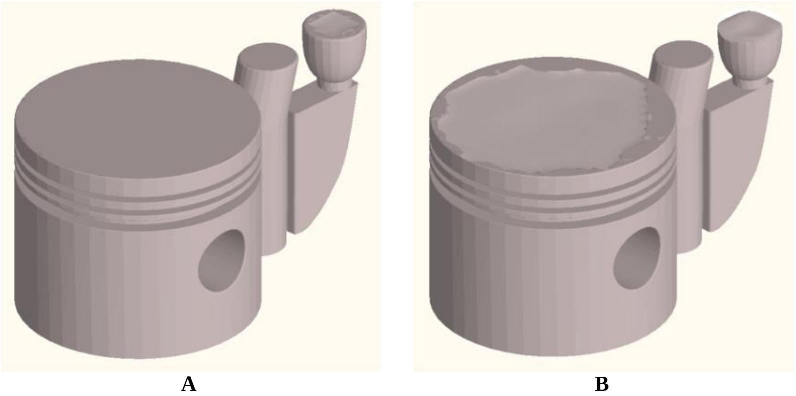


Figure 13 – The cast iron piston (A) and the aluminium piston (B) after metal mold casting (the feeding point is provided).

Adding of the feeding point in the field of the piston skirt provides complete filling of the metal mold by melts of gray cast iron and aluminium. Time casting of the cast iron piston was amounted to 30.963 s, time casting of the aluminium piston was amounted to 26.819 s. Volume shrinkage of gray cast iron EN-GJL-300 after cooling into the metal mold is observed only into the gating system. Volume shrinkage (about 3%) is observed on the head of the piston after cooling of aluminium alloy A356. Therefore, casting of the aluminium pistons it is necessary to perform taking into account allowance for subsequent machining to the required size according to a part drawing.

The pistons castings of the automobile made of grey cast iron EN-GJL-300 and aluminium alloy A356 after partial horizontal casting with same flow of melts and subsequent tilt of the metal mold at the given angle are presented in the Fig. 14.

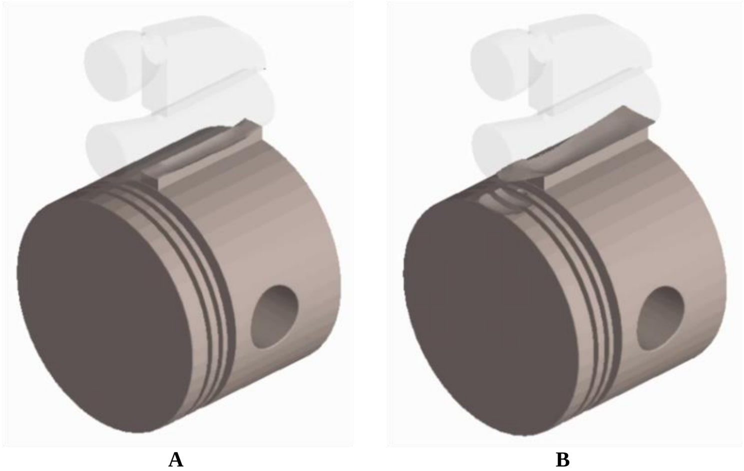


Figure 14 – The cast iron piston (A) and the aluminium piston (B) after casting with the metal mold tilt by 90 degrees.

Melts of gray cast iron and aluminium were poured into the metal mold by 80% and 85%, respectively. Downtime after filling of melts wasn't set. Melts remained in liquid condition due to short duration tilt of the metal mold (0.3 s) by 90 degrees. Time of metal mold casting is increased on 5 s due to increasing of filled volume of aluminium melt by 5%. Materials saving by 15 – 20% occur due to displacement of melts from the gating system into the cavity for filling of the metal mold. However, calculated volume shrinkage of materials after casting by this method is formed to a greater extent than volume shrinkage after horizontal casting (for example, with adding of the feeding point).

The pistons castings of the automobile made of grey cast iron EN-GJL-300 and aluminium alloy

A356 after casting with same flow of melts and two mirror located vents are presented in the Fig. 15.

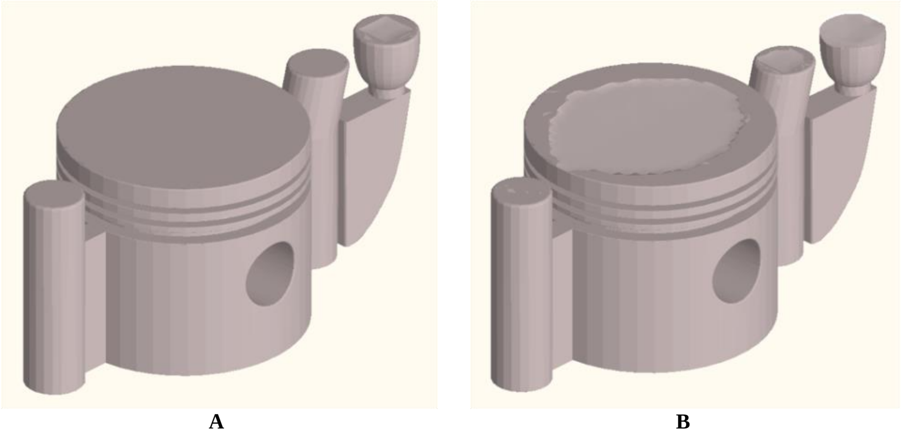


Figure 15 – The cast iron piston (A) and the aluminium piston (B) after casting with two vents into the gating system.

Adding of the second vent leads to filling of all volume of the metal mold by melt of gray cast iron and formation of material shrinkage only into the pouring basin. The casting shrinkage of the aluminium piston is observed on the head, the vents and the pouring basin. Volume shrinkage of the cast iron casting is formed to a lesser extent (in 4 times) than volume shrinkage of the aluminium casting. Casting of the aluminium piston occurs more rapidly (on 8 s) than casting of the cast iron piston.

The pistons castings of the automobile made of grey cast iron EN-GJL-300 and aluminium alloy A356 after casting with same flow of melts and at changing of the castings orientation into the metal mold are presented in the Fig. 16.

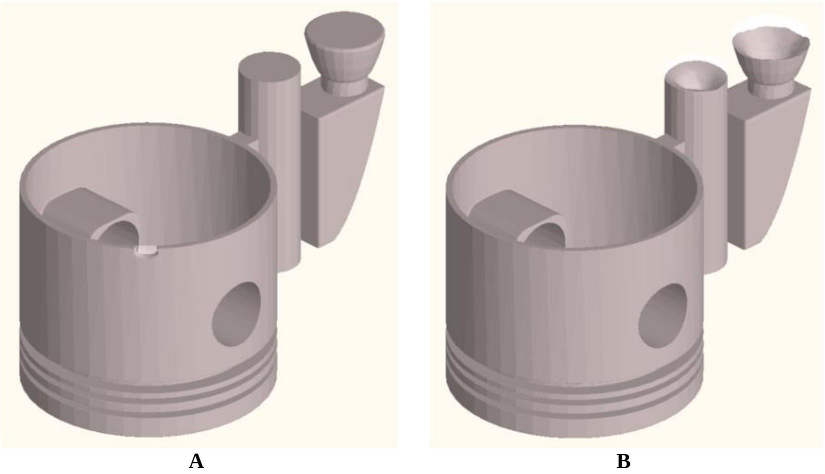


Figure 16 – The metal mold casting at changing of the casting orientation: A – grey cast iron EN-GJL-300, B – aluminium alloy A356.

Changing of the casting orientation into the metal mold (by 180 degrees) provides complete filling of the mold by aluminium melt. Volume shrinkage at this casting method of aluminium alloy A356 is 3.78%. However, changing of material volume is observed into the gating system of the metal mold. Incomplete filling (approximately 1.5%) into the piston skirt is observed at casting of grey cast iron EN-GJL-300. The casting process of the aluminium piston lasts on 1.7 s less than the casting process of the cast iron piston.

Conclusion

Casting flaws were discovered after cooling of the cast iron and aluminium castings. However, volume shrinkage of aluminium alloy can lead to significant changing of the piston dimensions. Insufficient feeding by melt during metal mold casting can lead to formation of incomplete fillings into the cooled casting. Analysis of the condition castings after cooling into the metal mold allowed to determine the most rational methods of casting: for the cast iron pistons – the metal mold tilt by 90 degrees and subsequent cooling, for the aluminium pistons – changing of the casting orientation (by 180 degrees) into the metal mold. The castings must be processed mechanically after metal mold casting.

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