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Shaping the Structure and Properties of High Quality Silumin Castings in Metal Molds Cooled with Water Mist

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Abstract

The paper presents some aspects of the theory and technology of high quality silumin castings in metal molds cooled pointed with water mist stream. The results of the work relate to improvement of the properties of silumin casts by affecting the cooling of the liquid silumin in gravity cast in metal mold and the possibility of controlling the solidification and crystallization of the casting. The high efficiency required from the cooling system is a consequence of an optimal selection of parameters of the generated mist and the maximum use of the phenomenon of water droplets evaporation on the surface of the cooled mold. The study showed that sequential spot cooling with use of water mist, characterized by a wide range of control means and a high maximum heat transfer efficiency, enables to control the flow of heat between the casting and the mold and it allows for a layered solidification leading to the realization of the entire cast solidification in the expected way: directional or simultaneous. Consequently, the results are: improvement of the quality of the castings as a result of the elimination of defects and significant reduction in shrinkage porosity in the casting, an increase of the homogeneity and fineness of the microstructure, about 25% increase in the mechanical properties.

Keywords: Innovative materials and casting technologies, Cooling, Water mist, Permanent mold casting

1. Introduction

This paper presents results of the examination of selected theoretical and technological issues in receiving high quality silumin casts in molds cooled with a point water mist jets. The core point of the examinations is the application of the water mist as the coolant for some areas on the external surface of the casting mold. Receiving the heat flow was caused by evaporation of the cooled water droplets on the surface of the mold. This cooling process is more efficient than the heat transfer achieved with the flow of exclusively the water or the air.

The analysis of the current state of knowledge suggests that in the process of casting, solidification of the casting is the essential step of the heat exchange which occurs between the cast, durable form and the environment. It also determines the resulting type of the microstructure and the properties of the cast [1-4]. The most commonly used way to increase the intensity of solidification of the conventional casting in metal molds is to change the wall thickness and the outer surface of the mold wall. An increase in the intensity of the heat flow can be achieved by use of a forced circulation of air or water, spraying the outer surfaces of the mold wall or dipping the mold in water. In the pressure casting it is mainly a closed cooling system being used to stabilize temperature in the mold [5, 6]. Observation of the cooling of a

solid body's surface with a free flowing stream of water and air showed that this way of cooling allows for a particularly high heat flow (Bi >> 1) as well as favorable economic and regulatory aspects [7, 8]. In turn the increase in the cooling rate rises the silumin cast grain fineness and reduces dendritic eutectic interlamellar distances and significantly reduces the porosity of the cast. Moreover the large change in the neareutectic alloys causes a shift of the eutectic point from 12.5% to as high as 14%.
The aim of the study was to analyze the influence of the spot cooling of selected areas of the permanent mold gravity casting on the cooling of the mold and on the microstructure and properties of the silumin cast. For the studies there was the heat exchange analyzed during the cooling of the mold in the temperature of crystallization and during cooling down of the solid casting, as well as there was tested by simulating the impact of cooling with a water spray on the temperature change in the mold and casting.

2. Experimental

The study was conducted on a working station (shown in Figure 1).

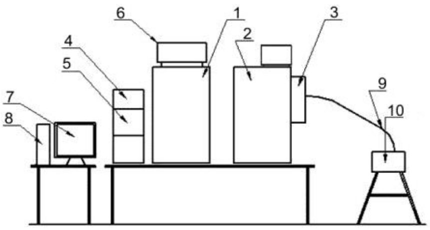


Fig. 1. The scheme of the research station: Modules: 1, 2 – air and water dosing, 3 – mixing of components, 4, 5 – supplying of air and water solenoid valves, 6 – computer cooling control, 7, 8 – PC, 9 – cooling circuit, 10 – research metal mold

The water mist was produced in the device (1, 2, 3) which dosed the appropriate amount of water and its dispersion in air by centrifugal spraying of water (Figure 2) in a stream of compressed air (3). These figures were determined by a computer-controlled valve (6) and recorded by flow sensors in the computer system (7). The final structure of the stream of water mist with selected flow parameters Pw and Pp, is also affected by the shape and cross-size of the emitting water mist nozzle, which is the end of the transport channel (Fig. 3b). The achieved technology enables the production of water mist pressure in range 0.05 ÷ 0.6 MPa air and 0.01 ÷ 0.4 MPa water and the water flow range from 0 to 850 l/min of air and from 0 to 0.6 l/min water in each of the cooling circuits (9).

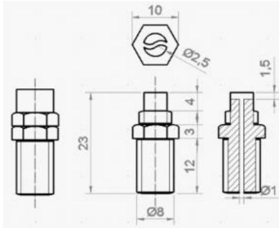


Fig. 2. Developed swirl jet

Research molds were made of: EN-GJL-200 EN iron, 1982 CuAl10Ni5Fe5 bronze and X37CrMoV51 (10) steel. With the iron and bronze molds the cooling process was examined of the casting and the mold plate both equally thick. To test the efficiency of the cooling water mist a steel mold with an electric heating element was used. Heat exchange was limited to a circular face, which was cooled by means of a spot-cylindrical nozzle. During the concurrent cooling the mold with a water spray and heating it there were made measurements on the electricity consumption.
The mold temperature field was studied using a thermal imaging camera Optris PI (Fig. 3c) and type K thermocouples placed in the wall of the mold and in the space between the mold and the cooling nozzles. A video of the water mist stream was recorded with a high-speed video camera (Fig. 3b) and with a regular camera. Developed images were analyzed graphically using a computer system with a statistical analysis of the image. Figure 2 shows the construction of the developed for the work water sprayers. The essential point of the design is the shape of the channel that swirls the water stream. Also the influence of the nozzles (steel pipes) emitting water mist of a circular section of range of 5 to 15 mm and rectangular section on the water mist stream geometry.

a) b) c)

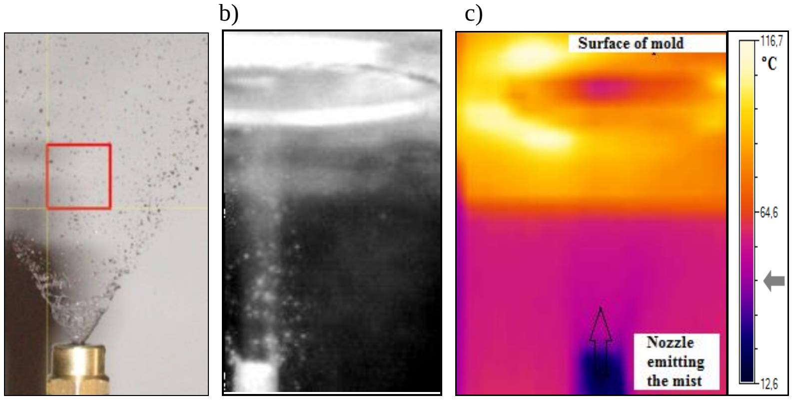


Fig. 3. Picture of :a) – water spraying with swirl jet (digital camera), cooled surface of metal mold with emitted water mist stream registered with use of: b) fastec camera, c) – infrared camera

Figure 4 shows the structure of the casting mold for examination of the formed castings with a wall thickness of 5, 10 and 15 mm (Fig. 4c) and a developed thin-walled mold for acquiring strength samples (Rm). The mold was cooled with a nozzle directing the cooling substance into the slots in the cylindrical sections shown in Figure 4b.

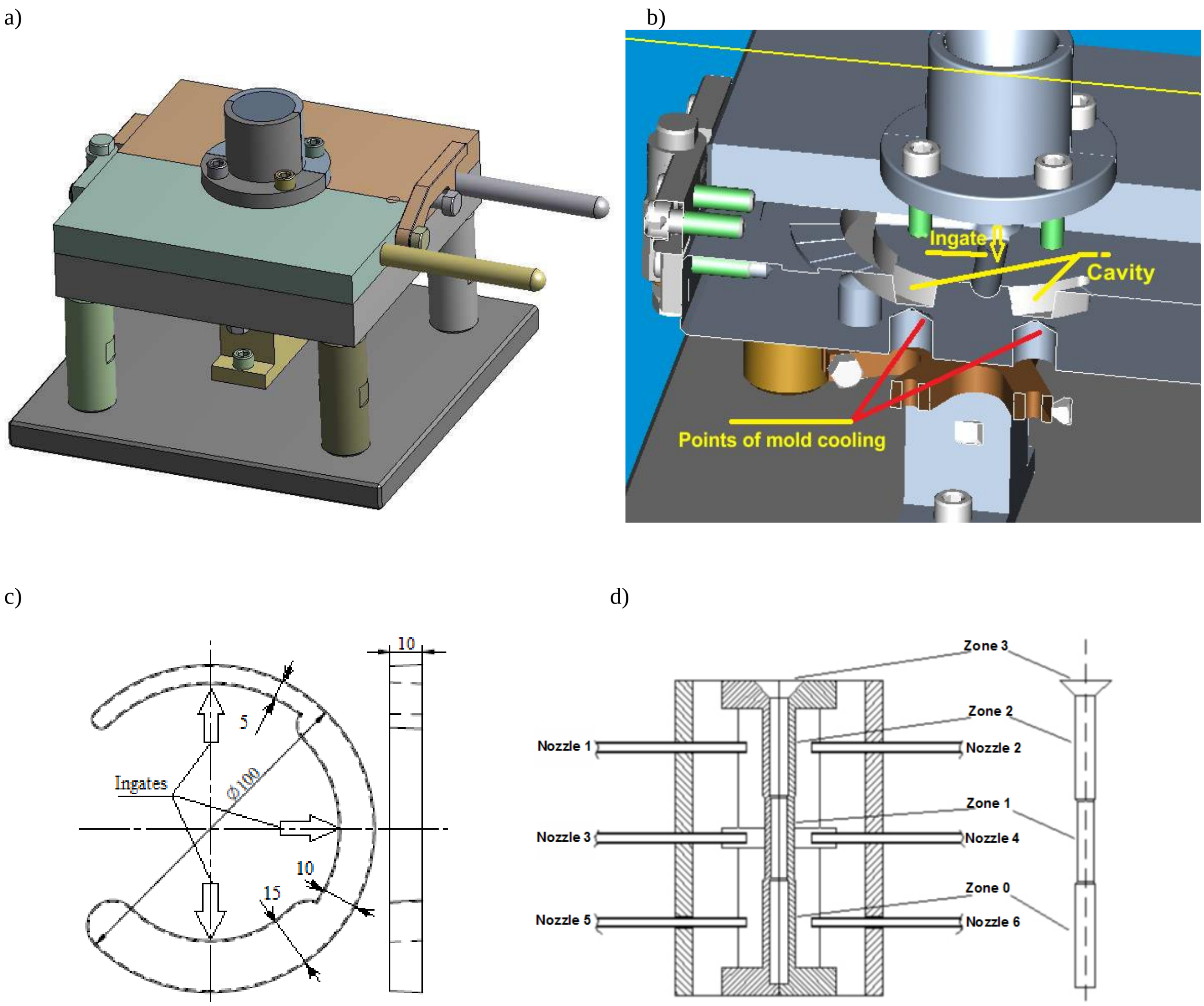


Fig. 4. Drawings of research molds: a), b), c) – for investigation of casting wall thickness 5, 10 i 15mm, d) – for “Rm” tests pieces

3. Results

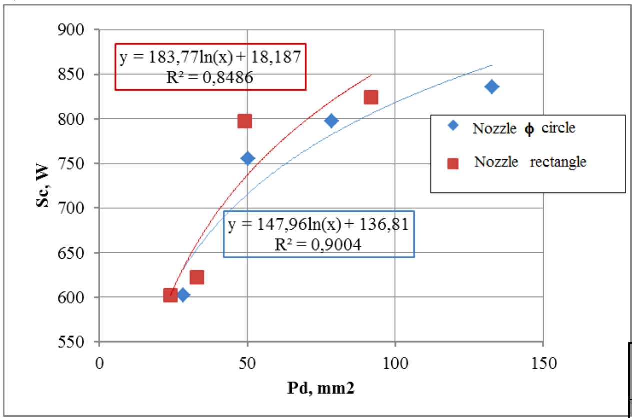
In this study there was examined: the impact of the flow parameters and the geometries of the nozzle and the water mist emitting spraying device on the efficiency of the water emitting and its effectiveness in cooling of the mold. Also the temperature distribution was examined in the area of the heat exchange between the nozzle and the receiving mold, and the influence of the varying water and air volumes in a stream of water mist was defined on the efficiency of the heat flow from the mold wall in the flow of 150÷350 l/min of air and 0.05÷0.24 l/min of water. The research made on AlSi11 AlSi9Mg _ AlSi7Mg silumin casting allows determining the effect of mold cooling water mist on the structure and properties of silumin casts.

3.1. Efficiency of water mist production and cooling of mold

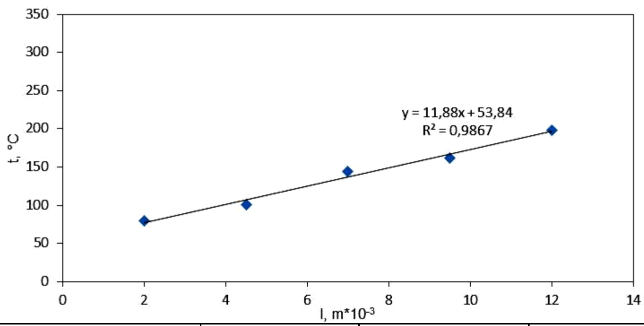
The research on efficiency and the emission of spraying water mist from the cylindrical nozzle showed that swirl atomizer in the range 0.2÷0.6 l/min of water provides effective water spraying and a control to the values of the angle of the spray stream in the range of 51÷76 degrees. Increasing the nozzle outlet’s diameter in the range of 1 - 2 mm causes an increase in spray angle and in the size of the water droplets. Raising the air flow in the range 150÷200 l/min causes about twice the decrease in the size of water droplets in the mist of water. In addition, the increase in the air flow in the range from 150 to 350 l/min and the flow of water in the range from 0.2 to 0.6 l/min enhances the flow speed of the water mist, wherein the average velocity of the droplets varies in the range from about 4 to 6 m/s. Changing the type and the geometry of the nozzle and the flow values of air and water allows to control the efficiency of generating the water mist. Regression equations can be used to describe the water mist's parameters as a function of the flow speed of air and the water droplet size obtained from the swirl jet. Figure 5 shows the influence of the diameter of the nozzle (Fig. 5a) on the stream arriving at the mold and the temperature gradient in the wall of the mold, received heat stream taken by the water mist with parameters 350l/min air and 0.16 l/min water.

The study on cooling efficiency in terms of a constant heat exchange determined that the mold cooled with an air stream flow at 300 l/min causes a temperature gradient in the mold wall thickness of 7.36 * 10^3 K/m and allows dissipating through the test mold surface a heat flow of 493 W. However, the use of water mist increases over 2-fold the mold's wall resulting temperature gradient to 11.88*10^3 K/m and the heat flow received to 1,090 W. Increasing the amount of water in the water mist boosts much more the heat flow than adding more air to the water mist. The analysis of the influence of the type and size of the nozzle shows that the bigger the diameter in the round nozzle as well as the rectangular nozzle is, the more heat transfer is produced from the cooled mold.

a)



b)



Air flow, l/min	Water flow, l/min	Gradient, (K/m)*10^3	Heat flux, W
350	0,16	11,88	1090

Fig. 5. Influence of jet area emitting the water mist (a) on heat flow received from metal mold, influence of water and air quantitiy on temperature gradient and heat floe received by water mist with parameters: 350 l/min of air and 0,16 l/min of water

In the thermographic studies (Fig. 3c) on the interaction of hot mold surface with the water mist stream during the cooling process showed that the stream of water mist is perpendicular at the collision with the surface of the mold and move radially on the surface of the mold with simultaneous evaporation of water droplets. The lowest temperature in the test (about 18°C) was recorded at a distance of 5 mm from the edge of the nozzle. In addition, studies have shown that cooling the mold preheated to the temperature of 400°C results in its rapid cooling. Initially the mold cooling rate is about 10 K / s, then decreases, and after 50 seconds at the temperature of 176 °C is less than 0.3 K/s. Then, in the boundary layer the temperature stabilizes in the mold between 24 and 27°C. In the central part of the heat exchange area the boundary layer thickness with a higher temperature is reduced probably because of the high kinetic flow of water mist. With distance from the axis of the incoming stream towards the mold, the water mist temperature rises and thus cooling efficiency drops. A comparison of the temperature at a distance of 20 mm from the mist stream is apparent that an increase from 3 to 10 mm in distance from the surface reduces the temperature of the mold in the surface layer by only about 1°C. This means that as the distance from the axis of the incoming stream grows the boundary layer thickness with the isothermal temperature distribution increases and thus the effectiveness of the mold cooling drops. In addition, studies have shown that stream of cold water mist drifting off the surface has a temperature higher in the first few seconds of cooling, that is between 17 and 86 °C and then lower between 24 and 41 °C.

The study shows that the droplets in the lower temperature range wet the surface immediately and evaporate from it evenly. As the temperature rises above 126 °C the wetting process recedes.

Water droplets are separated from the hot surface by a produced layer of steam and heat transfer is much slower. Based on all the observations there could be developed a relationship between the mold temperature and the effect on the average duration of the evaporation of the water droplets. The resulting Leidenfrost-phenomenon temperature is about 170 °C. This phenomenon may also explain the occurrence of the temperature difference between the heated surface and the saturation temperature of the liquid $\Delta T = 10 \div 100K$, the change the type of bubble boiling on the surface caused by the formation of the heating steam insulating layer of the liquid. This phenomenon is accompanied by a huge change in the density of a stream heat transfer.

Conclusions derived from the research on the mold surface impact on individual droplets of water were confirmed by the observation of the behavior of the water mist stream on the surface of the mold depending on the temperature and the flow of water and air in the water mist. In the case of a cold wall of mold the water mist wets the whole or part of its surface. An increase in the mold temperature and a decrease of water mist flow results in a reduction or disappearance of the effect of wetting the surface of the hot mold.

3.2. Modelling and simulation

Figure 6a shows the temperature field in the system cast-gap-mold chilled with water mist. The research indicates that on the point of contact of the casting and the mold an air gap formed, which is the thermal resistance in the exchange process. The temperature difference between the casting and the chill is over 200 °C for an initial period of cooling. The work carried out for this paper shows the presence of a temperature difference on the total mold's thickness.

The large difference in temperature (90 to 240 °C) between the casting and the chill plate is probably due to the shape of the casting, low coefficient of heat transfer through the gap, which for air is 0.025 W/(m·K) and is much lower than for aluminum alloys (150 W/(m·K)), or steel (50 W/(m·K)).

The developed for the study: range of variation of the heat flow received from the cooled surface with a water mist and the calculated heat transfer coefficient α (about 1÷15 $kWm^{-2}K^{-1}$) indicate that the heat transfer can take place in a context of a very high intensity characterized by Biot value: Bi >> 1 [2].

An analytical model was developed displaying the cooling process and temperature field in the system containing a solidifying cast in a mold cooled with a water mist which is all shown in Figure 6b. It assumes that the casting of the liquid metal at a temperature of pre-heated mold t t_p (t> t_p) starts the penetration of the mold by the heat flow (q_c), which lowers the temperature of the molten metal to the liquidus. At the same time it causes an increase in the temperature gradient in the thickness of the wall of the casting mold. Having started cooling the outer surface of the mold with water mist it receives the heat flow (qo), mainly due to the evaporation of water droplets (q_{par}) enhanced by convection heat emitted from the nozzle at a pressure (p (r)), and high velocity stream of water mist, and a small degree as a result of radiation mold (q_r). Cooling lowers the temperature of the mold and increases the temperature gradient in the thickness of the mold wall and a temperature and growth from 18 °C to 27 °C of the stream of steam and air flowing out from the heat transfer region. End of crystallization due to the depletion of casting molten metal finishes heat coagulation (q_{krz}) in the exchange process, accelerates the cooling of the casting (q_{st}) and reduces the temperature gradient in the wall of the mold.

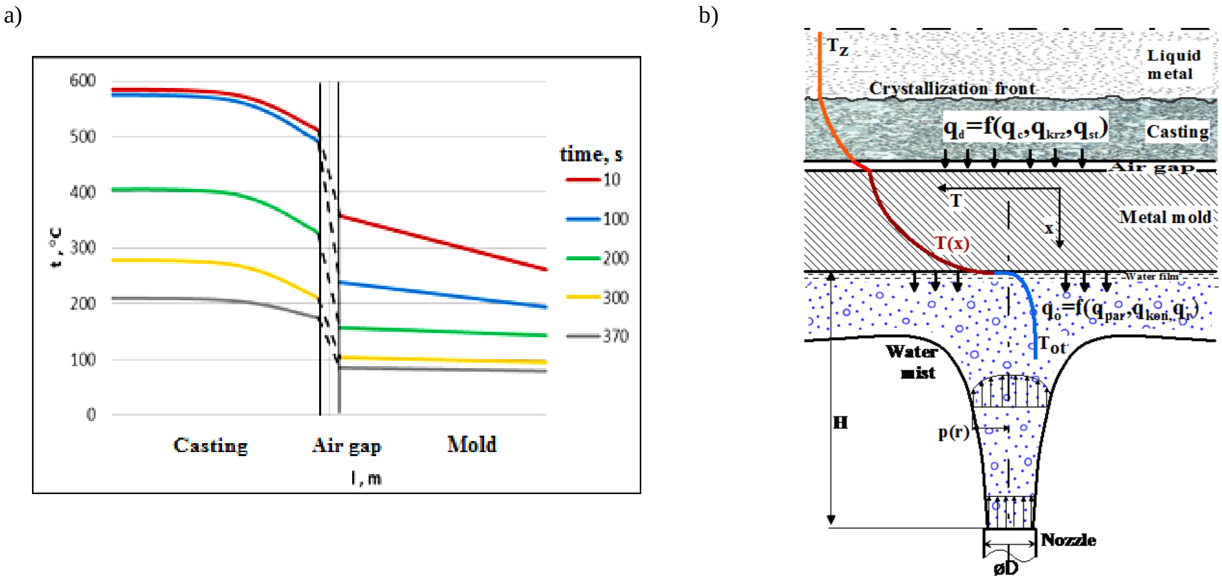


Fig. 6. Thermal field of mold – casting taking into account the air gap creating (a) and analitical model (b) for a cast cooled with water mist

The mathematical model and the calculated values of the coefficient α have been used to model a 3D mold to simulate the heat transfer process during silumin casting in a shaped mold sequentially cooled with a water mist. In Figures 7a-f there are examples of the results of the simulation performed in ANSYS.

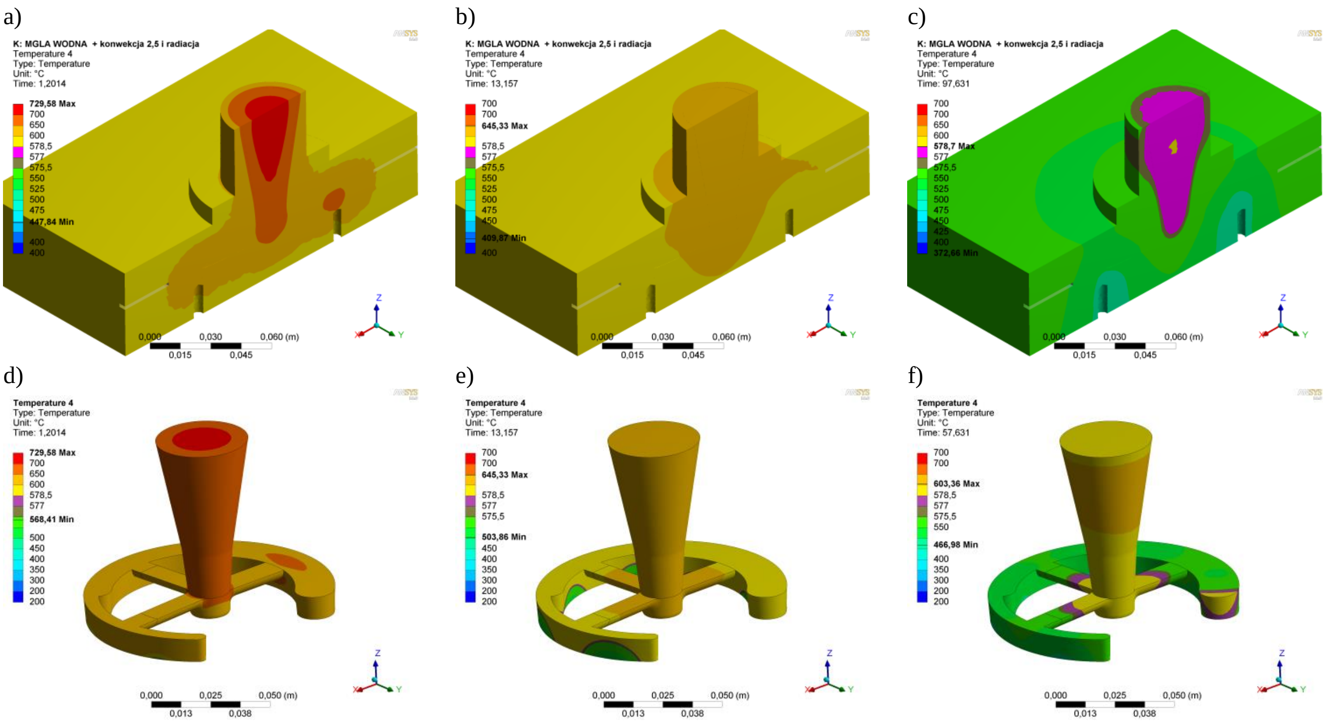


Fig. 7. Results of simulation of metal mold (a-c) and cast (d-f) cooling down made by Ansys computer software

The simulation tests show that the applied point water mist cooling on a preheated steel casting mold strongly affects the solidification of the silumin. The resulting temperature field in the casting mold for selected conditions allows for an analysis and a choice of the optimum casting system and designing strategies on locating the cooling nozzles and the sequence of their actions to achieve the desired type of a directional and simultaneous solidification in the casting regions.

3.3. Structure and properties

Figure 8 shows a comparison of cross-section thick castings made without cooling and with mold cooling using water mist. The research shows that the design of the casting has a high average wall thickness and contains several areas of change through the wall. This causes a large amount of cavities and shrinkage porosity.

Making the castings in the mold cooled with a water mist significantly reduced the amount of shrinkage defects. In addition, the feeding of the casting was considerably more effective during the pouring in the gate, in which there was a clearly visible drawhole surface, indicating a contraction compensating of casting. The porosity in the bottom of the axial casting decreased or completely disappeared.

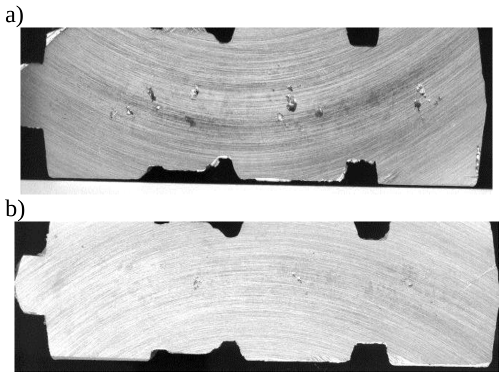


Fig. 8. View of casing section surface made of AlSi11 alloy in mold: a) – uncooled, b) – cooled with water mist stream

Figure 9 shows macroscopic images of microsections surface of cast samples made in permanent mold - uncooled and cooled with water mist. These studies demonstrate that the increased cooling rate obtained by cooling the casting mold reduced thte casting's gas porosity.

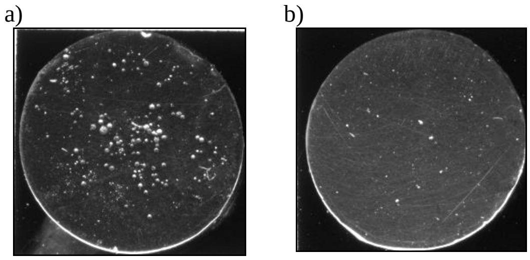


Fig. 9. Porosity of „Rm" test piece, size: ϕ10: a) – uncooled, b) cooled with water mist stream

Figure 10 shows a representative microstructure of the cast made of AlSi11 alloy obtained sequentially in the mold cooled with water mist flow of air / water 350/0.12 l/min and Figure 11 shows a statistical image analysis results of the cast microstructure. The research shows that the microstructure of the casting produced in a cooled mold is much more refined in comparison with the cast's microstructure produced without cooling.

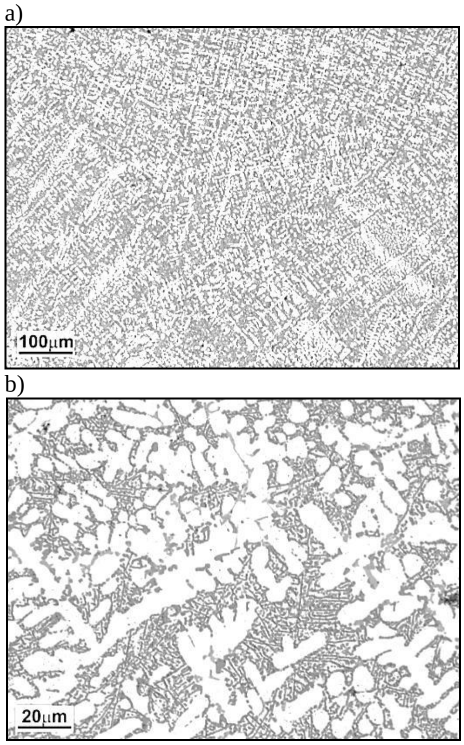


Fig. 10. Microstructure of the cast made of AlSi11 alloy achieved by use of water mist sequential cooling of permanent mold. Dendrites of α phase, eutectic α+β

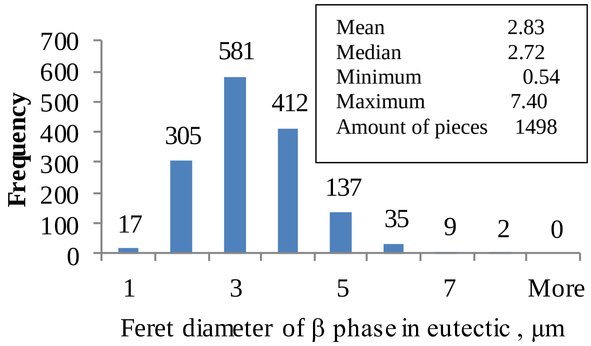


Fig. 11. Histogram of distribution of eutectic precipitates β phase

This shows a clear difference between the boundary layer and the middle layer. The average size of eutectic precipitates for the middle layer casting wall thickness is 2.86 microns, while the boundary layer is 2.33 microns. A large number of very small eutectic precipitates in the range of 2 to 3 microns is present in the core of the casting wall, probably due to the phenomenon of segregation of the microstructure. The analysis of the microstructure and the histogram β phase precipitates in the boundary layer shows the presence of a large diversity of microstructure. On the border of the middle layer in the microstructure are large, 7÷8 m β phase plates and large freely growing dendrites α phase.

The study characteristics Rm, $R_{p0.2}$, HB, A_5 of silumin casting result that mold cooling water mist causes about 25% increase in mechanical properties. From the Figure 12 of AlSi11 castings test one can draw a conclusion that the increase in strength depends on the multipoint cooling sequence of permanent mold (M2-M4). The highest values are achieved for sequences M4 priority mold cooling zone 1 (Fig. 4d), which were: Rm = 222 MPa, $Rp_{0.2}$ = 119 MPa, A_5 = 2.6 % i HB = 86.

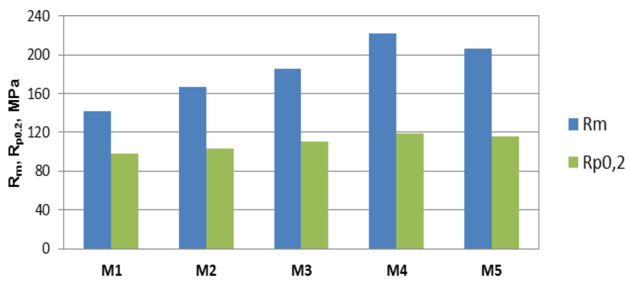


Fig. 12. Tensile strenght Rm and yield strenght $Rp_{0,2}$ of castings made of AlSi11 alloy in metal mold: M1 – uncooled, M2 – M5 – cooled with water mist stream.

4. Conclusions

The study showed that the use of open cooling water mist system of metal mold allows to obtain high-quality silumin castings with enhanced mechanical properties.

Improving the quality and mechanical properties of the casting is caused by a strong interaction with water mist cooling system resulting maximum use of the phenomenon of evaporation of water droplets on a chilled surface.

Developed cooling system has a broad scope and high value of the maximum heat transfer efficiency by allowing layers solidification leading to the realization of the entire cast expected type directional solidification or simultaneous one.

Improving the quality of casting is obtained as a result of the elimination of defects and significant reduction in shrinkage porosity in the casting, increasing the homogeneity and fineness of the microstructure, and about 25% increase in the mechanical properties and shortening of the die-casting process.

Results of investigations of cooling efficiency of the mold with water mist that were carried out using a thermal imaging camera and it allowed to calculate values the heat flux received from the mold and the range of changes of heat transfer coefficient α. The results have enabled development of regression equations correlating the received value of the heat flow to the parameters of water mist flow and the mold's temperature.

The simulations in a one-dimensional system and 3D demonstrated the applicability of the model to the studies on the solidification process and cooling of the mold and the casting as well as the casting technology and for forecasting the parameters in metal molds cooled with water mist for simple plate-like casts as well as the for the casts of a complex construction.

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