Control of the formation of structural properties of hypereutectic aluminum alloys during injection molding with crystallization

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Abstract. The paper presents the results of the research aimed at developing an automated control system for the process of forming the properties of metal products under the conditions of pressure application on the crystallizing metal. The results of the work are related to the automated control system for technological processes (ACS TP) and can be used in the manufacture of internal combustion engine pistons from alloys based on aluminum with a high silicon content. The object of control is molten metal, the technological equipment is a hydraulic horizontal press for casting with crystallization under pressure. The paper shows the possibility of controlling the formation of the properties of the final product. The results of the work are confirmed by the example of studies of the microstructures of the obtained samples. The method for applying pressure to a crystallizing metal and the way to control this method are proposed.

1. Introduction
At present, the processes of crystallization of aluminum alloys with a high silicon content are complex and not sufficiently studied [1, 2]. The crystallization of these alloys leads to the formation of product properties. Crystallization includes the processes of heat and mass transfer, phase transformations, various chemical reactions, release of dissolved gases, etc. [3]. In addition to the listed processes, casting defects are formed during crystallization, namely: liquation, porosity, gas and shrink holes [4]. These defects negatively affect the values of hardness, plasticity and elasticity, the formation of the structure. Today, the solution to the listed problems is rolling and forging and stamping production, where, using forging, rolling and plastic deformation technologies, physical and structural properties are brought into line with the specified ones [5].

When conducting the scientific and technical review, it became clear that the currently existing automated control systems for casting processes are not effective and are not able to completely prevent the formation of casting defects [6]. Such automated control systems cannot provide measurement, control and adjustment of technological parameters in real-time.

The task of the work is to monitor the change in the temperature of the metal and mold during crystallization under pressure, and in case of deviation of the obtained values from the specified ones, make changes in the control program.

2. Main part
The proposed solution relates to foundry and can be used to control the formation of structures and properties of aluminum alloys.
In the process of researching scientific and technical information [7-14], it was found that the closest technologies in relation to the developed one are methods of controlling the crystallization process during injection molding, which include heating of the metal to a temperature above liquidus, pouring liquid metal into the vacuum treating mold cavity through casting, applying pressure on liquid metal, metal sealing and holding under pressure. It must be said that in most cases, pressure is applied with an increase to 500 MPa at speed of 120-125 MPa/s and intervals of 0.5-0.1 s. Holding of the metal under pressure is carried out until the alloy is cooled to 100-150 °C. In this case, the magnitude and speed of pressure application are changed depending on the pressure sensor readings. The sensor is built into the hydraulic system of the technological equipment. As a rule, a hydraulic press is the equipment.

In the process of performing the research, the task is to obtain a high-quality metal structure in the entire volume of the obtained blanks from a hypereutectic aluminum alloy using the modern process control system.

The problem solution is the use of the developed technology for pressure application on the crystallizing metal, which includes preparing a melt of the given chemical composition, overheating it by 200 °C, and then pouring the required volume of metal into a vacuum-treated mold. Before pouring, the mold is heated up to a temperature of 250 °C. After this the crystallizing metal is pressed with press plungers moving towards each other under a pressure of 500 MPa.

The process scheme and the automated control system are shown in figure 1.

![Figure 1. Process diagram and automated control system for the process of applying pressure on the crystallizing metal.](image)

Legend: FC - frequency converter, PLC - programmable logic controller, PS1 - position sensor, PS2 - pressure sensor, HA - hydraulic accumulator.

The magnitude of the pressure in the hydraulic system, and, consequently, the magnitude of the pressure imposed on the crystallizing metal is controlled through the values coming from a thermocouple installed in the mold and controlling the temperature of the metal under pressure testing.
The control system includes the software developed by the author and the power unit, presented in the form of a control cabinet (CC). This control cabinet provides reception, processing and transmission of information about the process to a PC (figure 2).

![Control cabinet](image)

**Figure 2.** Control cabinet.

The control cabinet contains the following:

- programmable 8-channel ADC;
- industrial power supply for converting AC voltage 220V to 24V;
- automatic switch.

As for the hardware, it is implemented on Siemens controllers and fully complies with the GOST (State Standard) R 51840-2001 (IEC 61131-2).

The creation of the controllers' software algorithm is implemented in Siemens environment CoDeSys v.2.3.x. Programming language - ST.

The implemented mode for controlling the system with controlled pressure application can be attributed to systems with discrete (finite) time [15]. In fact, the very characteristics of the object being controlled are unknown. This system makes decisions based on the values of the control law. All continuous time is divided into appropriate cycles. In turn, the cycles are divided into steps. The discrepancy between the given action and the value at the output of the control object, in our case, will be taken as a value at the input. Next, you need to turn to the estimation algorithms. These algorithms are based on the law that was originally set. As a result, the signal indicating a discrepancy is processed and analyzed based on all cycles. The set indicator is directly related to the accuracy value, as well as to the quality of the adjustment itself. During recognition using a set indicator, which is measured and calculated by the control TP, either at each step, or based on the full range of steps, an automated sample of the model of the evaluation process can be generated.

The control is realized with the help of the given algorithms. These algorithms are closely related to each other. This is based on a selection (filtration) of input values in the system itself, as well as on the adaptation of the structural model and the parametric one. These models are automatically implemented.
Also, communication is based on the calculation of the most optimal values of the control system. This also occurs in the automatic mode.

Next, the state is assessed; the values of the technological process (TP) and the parameters of the control object are identified. This process is based on the data obtained from the thermocouples (figure 3).

![Figure 3](image_url)

**Figure 3.** Registration of metal temperature values in the process of pressure application, where 1 is the mode without pressure applying, 2 is the mode with pressure application of 500 MPa.

With this assessment, it is possible to determine the very structure of the control law. In other words, it becomes possible to generate the principles of structural adaptation and adaptation by parameters.

Using the proposed method for controlling the process of pressure application, it becomes possible to control the formation of the metal structure. It is confirmed by microstructures of samples 1 and 2 (figure 4).

![Mode 1](image_url) ![Mode 2](image_url)

**Figure 4.** Microstructures of the AK18 aluminum alloy, where Mode 1 - without pressure application, Mode 2 - with pressure application of 500 MPa.
In the picture corresponding to Mode 1 (without pressure application), a coarse structure is observed, large inclusions, liquation, shells, porosity and shrinkage porosity are noticeable.

A completely different picture is observed when metal is processed according to the Second mode (pressure application of 500 MPa) - the grain is finer, there are no grain boundaries, the structure is denser, and there are no coarse inclusions.

3. Conclusion
The study of the obtained microstructures allows us to conclude that one or another metal structure is formed, depending on the pressure application mode. With an increase of the pressure applied to the metal, we obtain a denser casting with a uniform structure, and as a result, with a higher level of physical and mechanical properties.

By varying and controlling the magnitude of the applied pressure during the crystallization process, it becomes possible to change and, therefore, to control the formation of the basic structural and physical-mechanical properties of the finished product.

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