Automation of pressure imposing on the crystallizing metal

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Abstract. Crystallization as a process of forming the properties of metal products is studied as a multi-dimensional control object, at the entrance to which, along with temperature and time, pressure is considered as controlled and operated parameter. And at the exit such parameters include density of the metal and its mechanical properties. It is found out that the feedback control on volume change provides the maximum compaction of atoms in the crystal lattice.

1. Introduction

Crystallization of metals and alloys is a complex and still insufficiently studied process in which the properties of mass metal products are formed. This process includes heat and mass transfer, phase transformations, chemical reactions, the evolution of dissolved gases and non-metallic compounds, shrinkage, etc. [1-3]. Under conditions of gravity and uncontrolled removal of heat in the process of crystallization, segregation defects, loosening, porosity, gas and shrinkage shells occur, which negative influence on the properties is eliminated in the rolling and forging and stamping industries.

In this regard, the study of the possibility of effective management of the formation of the structure and properties of metals and alloys directly in the crystallization process seems to be an urgent scientific and technical problem.

2. The crystallization process as a multi-dimensional control object

In the metallurgical and foundry industries, the formation of the crystalline structure of ingots and castings occurs under the influence of two parameters - temperature and time, and the ability to control the cooling rate remains very limited.

If pressure is considered as a factor of external influence on crystallization, it is not only controllable, but also a operated in time. In interaction with controlled pouring temperature and initial shape temperature, the crystallization process translates into the discharge of multidimensional control objects (MDCO).

In this case, at the input the MDCO have the following parameters (figure 1): the temperature of the cast metal – $x_1$; the amount of pressure applied to the liquid and crystallizing metal - $x_2$; mold temperature before pouring metal - $x_3$; time - $x_4$. At the output MDCO have the following characteristics depending on the structure of properties: metal density - $y_1$; tensile strength - $y_2$; hardness - $y_3$; elongation - $y_4$. 
The mathematical model of the MDCO for the case when the dependencies of the outputs from the inputs can be represented by partial differential equations (in the Cauchy form) in the image domain can be represented as follows:

\[ y_1(s) = W_{11}(s)x_1(s) + W_{12}(s)x_2(s) + W_{13}(s)x_3(s) + W_{14}(s)x_4(s); \]
\[ y_2(s) = W_{21}(s)x_1(s) + W_{22}(s)x_2(s) + W_{23}(s)x_3(s) + W_{24}(s)x_4(s); \]
\[ y_3(s) = W_{31}(s)x_1(s) + W_{32}(s)x_2(s) + W_{33}(s)x_3(s) + W_{34}(s)x_4(s); \]
\[ y_4(s) = W_{41}(s)x_1(s) + W_{42}(s)x_2(s) + W_{43}(s)x_3(s) + W_{44}(s)x_4(s); \]

Here, the direct and cross links between the input and output parameters are represented through the corresponding transfer functions \( W_{ij}(s) \). The imposing of pressure is carried out within a few seconds, therefore, these relationships do not appear in statics, but they appear in dynamics and can be described by differential equations of the second and higher orders. Accurate control of the real-time output parameters by adjusting the input parameters will require making decisions that are based on solving differential equations for primitive functions and on determining all transfer functions in images.

It should be noted that a similar situation arises during control of other high-speed technological processes, when the delay of control actions depends on the inertia of the sensors and the speed of calculations. The way out is to control the deviation, i.e. adaptive feedback control. As for the system of equations (1) - (4), they can be used in developing the structure of the adaptive control system.

From the point of view of the possibility of improving the properties of the final product, it is of fundamental importance to manage such mutual arrangement and interaction of atoms, which ensures the formation of the largest possible number of effective interatomic bonds. Therefore, achieving high-density \( y_1 \) is important for improving other indicators of \( y_2, y_3, y_4 \) properties.

As for such input parameters as \( x_1 \) and \( x_3 \), on the basis of preliminary studies, their values can be fixed at a certain level, and their effect on \( y_1 \) in the formula \( W_{11}(s)x_1(s) \) is \( W_{13}(s)x_3(s) \) can be represented by functions \( K_{11} \) and \( K_{13} \), respectively.

Certainly, \( K_{11} \) and \( K_{13} \), from the point of view of physical processes in the crystallizing metal, are complex functions, but they depend on the parameters \( x_1 \) and \( x_3 \), which are controllable but not operated. Therefore, to investigate the influence of these functions is possible only in the experiment.

For fixed values of \( x_1 \) and \( x_3 \), equations (1), (2), (3) determine equation (4), and in equation (1) the components \( W_{12}(s)x_2(s) \) is \( W_{14}(s)x_4(s) \), determine by means of control the achievement of the control target by the parameter \( y_1 \rightarrow \text{max} \).

3. Shrinkage compensation mechanism at the time of crystallization

Imposing pressure on the liquid and crystallizing metal, obviously, brings atoms closer together and converts the metal as a system into a new thermodynamically unstable state. It is known that under the influence of pressure, the temperature of the onset of crystallization increases, and the cooling rate

![Figure 1. Control object model.](image-url)
increases. Crystallization from a strongly nonequilibrium state obeys the laws of synergetics (self-organization). The formation of crystallization centers and their growth must also be considered taking into account the spatial-geometric and purely mechanical components of the process. So, in the absence of pressure at the junction of high-angle grain boundaries, unfilled spaces appear [4]. The pressure compressing atoms is also capable of delivering atoms to the crystallization front and compensating for the decrease in volume during the transition of atoms from a liquid to a crystalline state. Crystallization under pressure with compensation of volume reduction, with achievement of higher density in comparison with crystallization under conditions of gravity, thus, depends not only on the distribution of temperature fields, on the cooling rate, on the magnitude and rate of pressure imposition, but also on controlling the volume change.

Consequently, the increase in density can be attributed to the volume of the metal that is pressed under pressure inside the crystallizing metal \( \Delta V \), and the relative volume change \( \varepsilon = \frac{\Delta V}{V_0} \), where \( V_0 \) is the volume of the filled metal, is called compaction of the crystallizing metal.

Moving from images to primitive functions, the control task associated with achieving maximum compaction of the crystallizing metal can be represented as follows:

\[
\varepsilon = f(p, \tau) \rightarrow \max
\]

By changing the pressure value at a given time interval, it is possible to act on metal atoms in different temperature ranges. It is established that the optimal rate of pressure imposing \( dp/dt = V \) for these values of \( t_1 \) and \( t_2 \) is, as shown in figure 2, in the interval between \( V_{\text{max}} \) and \( V_{\text{min}} \), when \( \varepsilon \rightarrow 0 \) (figure 2b.).

![Figure 2. Dependence of the degree of the metal sealing on speed and pressure.](image)
At a rate of imposing pressure of ~ 100 MPa/s, that part of the interatomic distances, which is associated with temperature, is likely to be removed - with the amplitude of atomic vibrations, after which the forces of mutual repulsion increase, the atoms freeze. Later in the cooling process, crystallization occurs without compensation for that part of the volume that occurs directly during crystallization. At the same time, $\varepsilon = 5 \ldots 6\%$ (figure 2a). At a minimum speed of ~ 30 MPa/s, shrinkage compensation lags behind the actual volume reduction (figure 2c). The maximum compaction of the metal is $\varepsilon = 12 \ldots 13\%$, as shown in figure 2b can be achieved when pressure is applied according to the program, which at all stages of casting formation provides pressing in such a volume of metal that is necessary to compensate for shrinkage, including shrinkage during crystallization.

In the process of starting manufacturing of a product, the law of imposing pressure is worked out taking into account more factors. The law ensuring $\varepsilon \rightarrow \max$ is implemented by the corresponding control program. This program can be used when re-starting production or when mastering the production of similar products. The corresponding control algorithm is presented in figure 3.

![Pressure imposing control algorithm](image)

**Figure 3.** Pressure imposing control algorithm.
4. Pulse Width Modulation (PWM)

The pressure on the metal being crystallized, as shown in [5], can be applied not only continuously, but with practically the same effect intermittently: 10 s - on state, 1 s - interrupt. Such modulation provides the ability to control the operation of the corresponding hydraulic cylinders in the transition mode, and varying the PWM parameters enhances the ability to respond to external disturbances.

5. Conclusion

The proposed system for controlling the process of applying pressure on the crystallizing metal is used practically in the production of cast billets for various purposes, mainly from deformable heat-hardened alloys.

By classification, this system is adaptive with feedback. Adaptation is achieved by adjusting the PWM parameters in the control program.

In the manufacture of products from alloy B95, a high degree of compaction of the metal in the crystallization process was achieved. With the value of ε = 12 ... 13%, the share of volumetric casting shrinkage accounts for 7 ... 8%, the elastic increase in the volume of the tooling cavity is 2..3%. So the compensation of shrinkage of the metal during the transition from the liquid to the crystalline state accounts for ~ 2 ... 3%. This indicates a significant uncompensated volume in the crystal structure, and hidden defects in interatomic bonds.

However, as it is shown in [6], the innovative potential of managing crystallization under pressure is not only improving all properties by eliminating such crystalline defects such as vacancies, dislocations, high-angle grain boundaries, zonal and interdendritic characteristic of traditional crystallization under gravity conditions, segregation, but also in controlling the formation of a quasicrystalline structure of alloys, in particular in alloys based on aluminium doped with transition metals (Fe, Ni, Co, Mn).

References

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