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Modeling of the Forming Process for Aluminum Detail

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Abstract: In the work, modeling of the forming process for aluminum detail was carried out. As a detail, "Pen" is chosen for which the material AK6M2 is determined, taking into account its physico-chemical properties. In the beginning, a 3D detail model is constructed, using the SolidWorks program. Then in the program Nova Flow, entire process of filling the mold in real time, rate of filling the mold cavity with metal, hardening time of the casting was determined. The temperature change dynamics of the casting after filling the mold is investigated. Possible nodes are susceptible to formation of shrinkage shells.

Keywords: modeling, molding process, casting, aluminum, part.

INTRODUCTION

Modern trends in the foundry production field require the creation of highly competitive products – cast blanks, with maximum quality indicators and minimal costs for the manufacturing process [1-5].

The current level of computing systems development makes it possible to create software complexes for the mathematical modeling of casting processes that solve complex technological problems.

High technical level of the product is achieved to a large extent at the functional design stage, which defines the main parameters of the object. The design solutions in this case largely determine its quality.

In case of inadequate study of the project, the costs of quality assurance, due to the need for subsequent design finishing, reach 10 ... 20% of the full products cost. At the same time, 50 ... 70% of the general product defects causes are associated with errors in design and engineering solutions, 20 ... 30% with technological deficiencies, 5 ... 15% are caused by workers. Therefore, the main task is to identify and eliminate potential sources of defects at the design stage [6-8].

The modern design methodology is based on the system approach. A technical object in the system approach is viewed as a complex system consisting of interrelated, purposefully functioning elements and being in interaction with the surrounding external environment. This allows you to take into account all the factors that affect its functioning, and to ensure the technical facility creation with high efficiency and quality indicators. One of the most important requirements of the system approach is the need to consider the existence and functioning of a technical object in time and space.

Foundry is one of the most important engineering branches. In various designs of modern machines and devices, about 70% by details weight are castings of steel, cast iron, copper, aluminum, magnesium and other alloys [9]. Especially great place is occupied by castings in the constructions of metallurgical equipment, turbines, forge-and-press machines, metal-cutting machine tools. In such an industry as machine tool construction, cast parts account for up to 90% of the total blanks mass. Wide distribution of foundry production is due to its advantages in comparison with other methods of manufacturing blanks. With the help of various casting methods, products of complex configuration can be obtained from any metals and their alloys, most of which cannot be obtained, for example, by stamping, forging or machining.

The configuration of the castings can be varied. It is determined by the ability to tooling and mold manufacture, minimum cavity thickness that the metal is able to fill, and the economic calculations that allow one to compare the manufacturing cost and operating casting conditions, on the one hand, and the like, produced in another way or composed of separate cast parts, with other.

MATERIALS AND METHODS

Related work

Modeling details from all sorts of metals – a topic that attracted the attention of many authors. The structure, details parameters, their materials, evaluation of strength and their features are an actual task.

In [10] description is given to different shaping variants of a part with an undercutting. A number of simulations of classical shaping schemes are provided to show the defects arising in shaping. A scheme of shaping with an elastic liner is proposed. The most rational method of forming workpieces with undercuts on the cylindrical part is found. It allows to change the stressed-strained state and avoid corrugations and folds in shaping.

A numerical simulation of thermodynamic processes for cryogenic metal forming of aluminum sheets and comparison with experimental results are described in [11]. Time dependent numerical simulations of the thermodynamic processes of cryogenic sheet metal forming covering all aspects of heat transfer through conduction, convection and radiation play a vital role in the design and development of future tools and are presented for several geometries.

In [12] metal plasticity and ductile fracture modeling for cast aluminum alloy parts are investigated. In this study, plasticity and ductile fracture properties were characterized by performing various tension, shear, and compression tests. A series of 10 experiments were performed using notched round bars, flat-grooved plates, in-plane shear plates, and cylindrical bars. Two cast aluminum alloys used in automotive suspension systems were selected. Plasticity modeling was performed and the results were compared with experimental and corresponding simulation results; further, the relationships among the stress triaxiality, Lode angle parameter, and equivalent plastic strain at the onset of failure were

In [13] determined to calibrate a ductile fracture model. The proposed ductile fracture model shows good agreement with experimental results. The morphology analysis was also carried out for the interested particles, and the geometrical parameters affecting the particle fracture were examined. By comparing the results of fractured and intact particles, found that there were some geometrical conditions for the fracture of silicon particles, and a certain magnitude of hydrostatic stress was required to break the particles.

Features of aluminum alloys for aluminum details forming

Features of foundry aluminum alloys are that they are divided into five groups [12, 14]. The best casting properties are the alloys of the 1st group – silumins. They have good fluidity, a small (0.9-1%) linear shrinkage, are resistant to cracking, are sufficiently tight. These alloys tend to form a coarse-grained eutectic in the cast structure and dissolve the gases.

Alloys of the second group are cuprum silumin. These alloys have quite good casting properties and higher strength than silumin, less prone to the formation of gas porosity in castings [12].

Alloys of 3 to 5 groups have the worst foundry properties – reduced fluidity, increased shrinkage (up to 1.3%), are prone to cracking, looseness and porosity in castings. Obtaining castings from these alloys requires strict adherence to technology regimes, ensuring a good filling of the mold, feeding the casts upon solidification [12].

All foundry aluminum alloys in a liquid state intensively dissolve gases and are oxidized [14]. When they solidify, gases are released from the solution and form a gas and gas-tight porosity, which reduces the mechanical properties and castings impermeability. The oxide film formed on the melt surface can break down when filling the mold and enter the casting body, reducing its mechanical properties and tightness. At high velocities of the melt in the gate system, the oxide film, mixing with air, forms foam that enters the mold cavity, leading to the defects formation in the casting body. The duration of casting times in the chill mold is determined taking into account its dimensions and mass. Typically, the castings are cooled in a mold to a temperature is about 400 ° C [14].

Mathematical model for calculating the aluminum details hardening

Data on alloys and materials of injection molds (IM), which will be stored in the database created when installing programs will determine the acceptable detail accuracy. To achieve more accurate results, it is necessary to "correct" some of the basic parameters in accordance with the "created" alloys and IM materials.

The model of package crystallization of the alloys, for example, the LVMFlow package, is based on a quasi-equilibrium theory. This is a macroscopic-phenomenological theory. Unlike pure metals, alloys crystallize in the temperature range from liquidus temperature to solidus temperature $(T_{liq} - T_{sol})$. In this zone (two-phase zone) there are both liquid and solid phases. The resulting solid phase is in equilibrium with the liquid phase [15, 16].

The low diffusion values of the elements coefficients in comparison with thermal diffusivity of the alloys and weakness of convective mixing make it possible to neglect the diffusion processes, both in the solid and in the liquid phases.

The state of a two-phase zone can be described with the help of macroscopic functions, analogous to temperature fields $T(r,t)$, speeds fields $V(r,t)$ [15, 16]. $T(r,t)$ and $V(r,t)$ – are local coordinates functions and time and take values in the range from 0 to 1. Their sum is 1 [15, 16].

$$S(r,t) + L(r,t) + P(r,t) = 1\,, \tag{1}$$

Where, $S(r,t)$ is the volume fraction of the solid phase; $L(r,t)$ is the volume fraction of liquid phase; $P(r,t)$ is the volume fraction of the void.

Then the mass balance in time derivatives looks like this: conservation law of mass reduces to the equation [15, 16]:

$$\frac{\partial S(r,t)}{\partial t} + \frac{\partial L(r,t)}{\partial t} + \frac{\partial P(r,t)}{\partial t} = 0\,. \tag{2}$$

Then the conservation law of masses reduces to the equation:

$$\rho_s(T)\frac{\partial S}{\partial T} + \frac{\partial}{\partial t}(\rho_i(T)L)\,, \tag{3}$$

Where, $\rho_s(T)$ – density of the metal solid phase, as a function of temperature; $\rho_i(T)$ – density of the metal liquid phase, as a function of temperature.

Further, the conservation law of the alloy components mass will be reduced to the form:

$$\rho_s(T)C_s^i(T)\frac{\partial S}{\partial t} + \frac{\partial}{\partial t}(C_j^i(T)\rho_j(T)L) = 0\,, \tag{4}$$

Where, $C_s^i(T)$, $C_j^i(T)$ – concentration of i-th alloy components at $i = 1,2\ldots n$ in the liquid and solid phases, which are in equilibrium at a temperature T.

The concentrations of the i-th components are determined from the phase diagram of the multicomponent system states.

Due to the flaw of data on the phase diagrams for multicomponent systems and also for simplifying the model, the two-component alloy model (Fe-C, Al-Si, Fe-Cr, Fe-Ni, Cr-Ni classes, etc.) was adopted as the base model with its basic two-component state diagram.

The displacement coefficients are input parameters for the alloys class.

The equations of the liquidus and solidus $C_t(T), C_s(T)$ are derived from the modified diagram [17]. We add the equation of heat conduction with sources and convective heat transfer.

$$S\rho_s(T)X_s(T)\frac{\partial T}{\partial t} + L\rho_i(T)X_i(T)(\frac{\partial T}{\partial t} VT) - q\rho_s(T)\frac{\partial S}{\partial t} = \mathrm{div}\,(\lambda(T)VT), \quad (5)$$

where S – volume fraction of solid phase; L – volume fraction of liquid phase; T – alloys temperature; V – speed fields; $\rho_s(T)$ – density of the alloy solid phase, which directly depends on temperature; $\rho_i(T)$ – density of the alloy liquid phase, which directly depends on temperature; $X_s(T)$ – specific heat of the alloy solid phase, which directly depends on temperature; $X_i(T)$ – specific heat of the alloy liquid phase, which directly depends on temperature; λ is the thermal conductivity coefficient of the alloy, which directly depends on temperature; q is the heat of alloy crystallization.

The thermal conductivity equation of outside the casting cavity – in the molded form can be expressed as:

$$\rho_k(T)X_k(T)\frac{\partial T}{\partial t} = \mathrm{div}\,(\lambda_k(T)VT), \quad (6)$$

Where, λ_k – thermal conductivity alloy coefficient of the k-th material for injection mold at $k = 1,2\ldots K$; $X_k(T)$ –specific alloy heat of the 1st mold material.

If we neglect convective heat transfer in equation (3), then equations (1– 4) form a closed system of equations for the functions: $S(r,t)$, $L(r,t)$, $P(r,t)$, $T(r,t)$ which describe the thermal model for LVMFlow.

Convective heat transfer can be neglected for small castings where thermal convection cannot develop and as a result, the cooling of the metal and heating of the mold during the mold filling are negligible.

The formation model of shrinkage defects is based on the percolation theory. This theory (percolation theory or percolation theory) is a mathematical theory used in physics, chemistry, and other fields to describe the emergence of connected structures in random environments (clusters) consisting of individual elements.

The dendritic framework of the two-phase zone exerts resistance to the flow of liquid that occurs during shrinkage.

The percolation (flow) rate of a liquid is proportional to the pressure gradient and carcass permeability [18].

The permeability of the carcass m(S) – function of the solid phase $S(r,t)$, in accordance with the percolation theory, turns to zero if the fraction of the solid phase is greater than the critical fraction of percolation $S > Sp$: $S(m) = 0$ [15, 16].

The percolation theory gives Sp –0.7 a value for the percolation threshold. The value of the percolation threshold $1 - Sp$ is entered in LVMFlow as an alloy parameter.

If the liquid phase is insulated in the casting during solidification, it is surrounded by a two-phase zone with a fraction of the solid phase > Sp, this phase cannot be fed by the liquid during the solidification process, and as a result, the continuity breaks and shrinkage begins.

In LVMFlow, the total shrinkage is calculated for each isolated liquid assembly and then it is distributed over an isolated fluid volume depending on the gravity field, zone permeability and temperature distribution.

If a localized liquid core contains a gating point, then it is considered that this zone is fed by the melt through the gating point and shrinkage cavities are not formed in this zone (the endless supply of feed metal).

Shrinkage formed in the zones with $S > Sp$ does not take part in the general shrinkage of the casting and forms a distributed porosity.

RESULTS AND DISCUSSION

Development of aluminum details

To create a 3D "Pen" detail of aluminum, the SolidWorks CAD software complex is used, which performs automation designer functions at the design and technological preparation stages of production. The SolidWorks editor allows you to create three-dimensional models of individual details, assembly units consisting of several details, and drawings by detail. SolidWorks can be used for modeling in three modes: detail, assembly, drawing.

When working in the "detail" mode, the required number of sketches for the base is first created, and then other elements are added. A drawing of the "Pen" detail is shown in Figure-1.

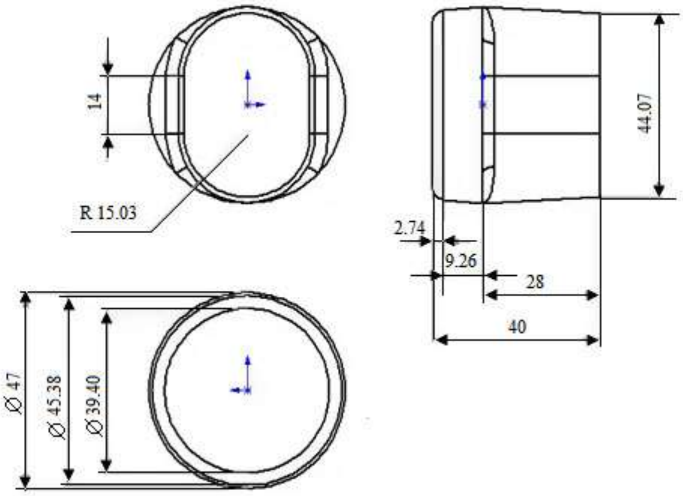


Fig-1: Drawing of the "Pen" detail

The created 3D model of the "Pen" detail is shown in Figure 2.

Fig-2: Created 3D model of "Pen" details

The position of the casting in the mold and the mold connector must ensure the high casting quality, minimum costs for its manufacture and for machining, minimum metal consumption and possibility of mechanization and automation of the technological process. In addition, we must strive to ensure that the castings size, which are subject to more stringent requirements for accuracy, do not intersect with the line of the mold connector.

The casting position should be chosen so that when filling the cavity of the mold with a melt, ensure the maximum removal of gases, obtaining the exact casting dimensions, minimizing the likelihood of shrinkage and gas defects formation. The number of connectors must be the smallest, and the connectors must be flat. The connector of the mold should ensure reliable fastening of the rods. Casting in the mold should be placed so that the overall height of the mold is the smallest. Also, the form connector should provide the least amount of defects in the distortions, in order to reduce the amount of finishing work. The length of the foundry joints should be minimal.

When the model is less than 250 mm high, the metal is transported along the plane of the connector to the flange part. The connector plane must be carried along one of the flange surfaces in order for the models "top" and "bottom" to be removed. Since the flange has a planar and shaped surface, therefore, in the lower part we leave a figured surface.

The order of "supply of metal" execution to the "Pen" details (Figure-3):

- On the "Front" plane, create a sketch of a rectangle 36 mm by 50 mm with rounded corners on the side of the detail.
- Using the "Extruded boss / base" tool toolbar "Elements", draw the drawn sketch 15 mm at 15 ° degrees in both directions.
- Create on the plane "Front" a sketch of the rectangle entering the part and a feeder with a width of 14 mm.
- Then, using the "Extruded boss / base" tool toolbox "Elements", draw the drawn sketch 10 mm at 15 ° degrees.
- After this, the edges of the previous element are rounded to 3mm.
- Above and below the connection of the feeder and detail, in addition to the back wall, a chamfer is made with a "Chamfer" tool at 1 mm and a 45 ° angle.

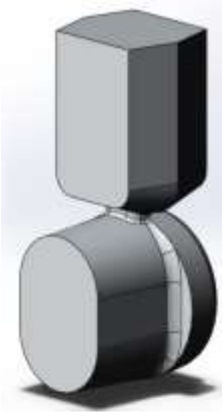


Fig-3: Created 3D model "Pen" details with "metal supply"

Such an casting arrangement makes it possible to effect a smooth filling of the mold with a melt, which excludes the melt streams destruction of the individual mold parts and the rod by the melt. The metal is transported along the plane of the connector to the casting part that is in the lower half-mold. Also, with such a connector plane, directional withdrawal of gases from the rod is created, which reduces the risk of gas defects in the casting. Simultaneous and uniform solidification is achieved by the supply of metal to the flange casting parts and by the arrangement of the feeders, which ensures symmetrical and uniform filling of the mold.

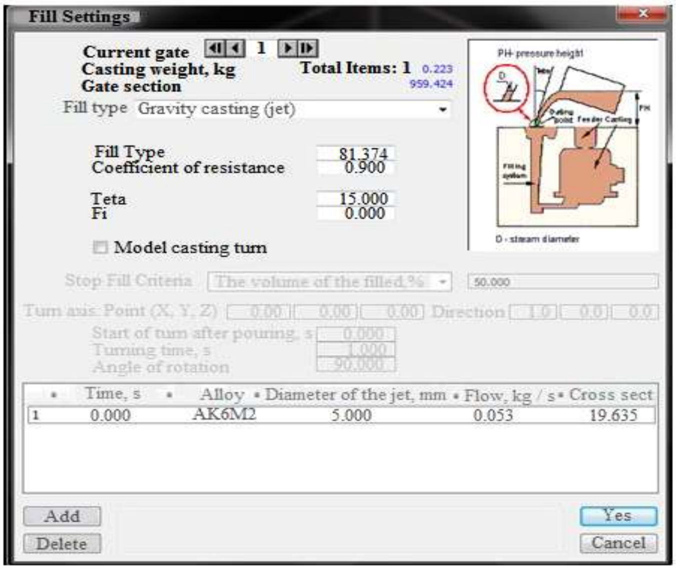
Mathematical modeling of the casting process for the "Pen" product

For the mathematical modeling of the casting process "Pen" is used NovaFlow. The NovaFlow package is designed for modeling casting processes in real shop conditions. Industrial alloys are overwhelmingly multicomponent systems. To model the crystallization of an alloy, its phase diagram is necessary. Unfortunately, there are no complete multicomponent state diagrams. The phase diagrams of two-component systems are sufficiently well studied. In this connection, in the "Database" module, an approximate calculation of the phase equilibria position of a multicomponent alloy is made by the deformation method of a two-component state diagram.

Mathematical modeling begins with the module "3D import". The module "3D import" carries out communication NovaFlow with CAD systems of geometrical modeling. The main purpose of the module is to convert STL files to the NovaFlow internal format.

Modeling the casting processes, the differential equations describing these processes are solved on the grid. The boundary conditions are in addition to the partial differential equation being solved and determine its behavior at the boundary of the region under consideration. Usually, the differential equation has more than one solution, and the whole family. The initial and boundary conditions make it possible to choose only one that corresponds to a particular physical process.

Next, the detail, with the set material parameters and the place of casting, is transferred to the module "Complete task". In the "Full Task" module, the parameters of the fill are set and the process of mold filling with metal and the casting solidification process in the full version is performed. The calculation process lasts until the casting is completely solidified. The window of the program with the modeling parameters of metal pouring is shown in Figure 4. AK6M2 was chosen as the material for casting detail, due to its physicochemical properties presented in Table 1 and Table 2 [17].



Current gate 1
Casting weight, kg 0.223
Gate section 959.424
Total Items: 1
Fill type Gravity casting (jet)

Fill Type 81.374
Coefficient of resistance 0.900

Teta 15.000
Fi 0.000

☐ Model casting turn

Stop Fill Criteria The volume of the filled,% 50.000
Turn axis Point (X, Y, Z) 0.00 0.00 0.00 Direction 1.0 0.0 0.0
Start of turn after pouring, s 0.000
Turning time, s 1.000
Angle of rotation 90.000

	Time, s	Alloy	Diameter of the jet, mm	Flow, kg / s	Cross sect
1	0.000	AK6M2	5.000	0.053	19.635

Fig-4: Parameters of modeling metal pouring

Table-1: Chemical composition of AK6M2

Silicon content (Si), %	Manganese content (Mn), %	Nickel content (Ni), %	Copper content (Cu), %	Titanium content (Ti), %	Aluminum content (Al), %
from 5.5 to 6.5	to 0.1	to 0.05	from 1.8 to 2.3	from 0.1 to 0.2	89.74

Table-2: Physical and mechanical properties of AK6M2

Condition	Relative elongation after fracture,%	Brinell hardness	Strength (Temporary resistance), MPa
Casting in chill mold	2	78.4	230

The chosen method of gravity casting (jet) is most suitable for simulating the casting of the "Pen" detail.

After setting the parameters of the filling, the hydrodynamic and thermal processes of the metal that takes place during the mold filling and its solidification are calculated. This process lasted about 1 hour. This indicator can be higher if you use a more powerful processor.

During the simulation, all the parameters listed in the list can be viewed: temperature, liquid phase volume, shrinkage localization, Nyam's microporosity, sensor information, hardening time.

After the saved calculation of the "Pen" detail, it opens in the "Passport Bank" module. "Passport Bank" is designed to save the results of modeling in the archive of technological solutions. For each casting a "passport" is entered, in which all the parameters of each simulation are recorded, which allows them to address them at any time.

The modeling of shrinkage formation is shown in Figure-5a. Simulation of the hardening time is shown in Figure-5b.

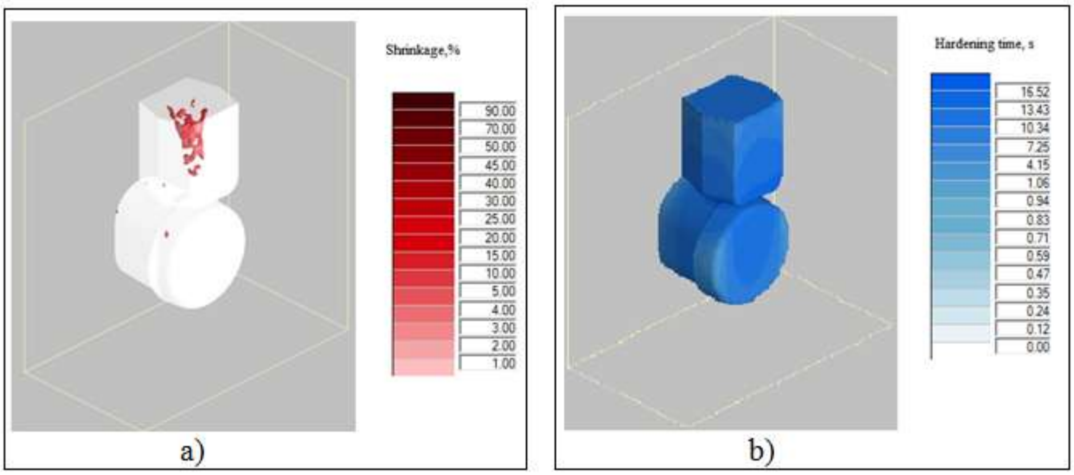


Fig-5: Mathematical modeling of shrinkage and melt hardening time

CONCLUSION

In the work, the forming process of detail from aluminum is simulated. A 3D model of the detail is built using the SolidWorks program.

In the NovaFlow program, entire process of mold filling, rate of filling the mold cavity with metal, hardening time of the casting have been modeled, dynamics of the casting temperature change after mold filling has been studied. Possible nodes are susceptible to shrinkage shells formation.

According to the obtained data, the mathematical model was obtained for the creation of the chill mold, and when analyzing the results, no contradictions were found with the physics of the process in the real foundry conditions.

The obtained data can be further used to optimize the existing technology, which will significantly reduce the time for design work and improve the quality of injection molded details.

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