COMPARATIVE ANALYSIS OF COMPUTER SYSTEMS FOR CASTING PROCESSES SIMULATION

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Abstract: Casting processes simulation is one of the advanced research tendencies of foundry production. This article analyzes the current state and prospects for the development of innovative computer technologies in the national and world foundry. The main directions of the strategy for the further development of the foundry are formulated. An overview of the most well-known systems for computer modeling of foundry processes is presented, which allow simulating and controlling the quality of castings to maximize productivity and minimize defects. However, the choice of software for casting processes simulation is of decisive importance, which requires reliable information about the capabilities of computer programs and the principles of their operation. The purpose of the study is to carry out a comparative analysis of the most well-known systems for casting processes simulation and the possibility of their use for various casting methods. The software tools were compared by purpose, functionality, the number of simulated technological processes, the numerical method used for solving the problems of differential equations in the shaping of the casting, as well as the degree of completeness of the factors taken into account in the simulation. The research results can serve as recommended guidelines for specialists and managers of foundries on the choice of the necessary software, taking into account their requirements and the special aspects of the casting processes.

Keywords: *casting process, computer modeling, casting simulation, software*

1. Introduction.

Foundry is the main base of the mechanical engineering and metallurgical complex, and its development depends on the pace of development of these industries as a whole. However, manufacturing cast parts with improved physical-chemical characteristics is a very important production task, which scientists and industrialists are aiming to solve.

Metallurgy and foundry are science-intensive, complex and interconnected industries. Metallurgists and foundry workers, in addition to the tasks of direct control of technological processes, in their activities are often faced with the need to perform rather complex technological and engineering-economical evaluations.

From the analysis of the current circumstance and prospects for the development of innovative technologies, it follows that to modernize the foundry, first of all, it is necessary to significantly increase the volume of investments in science: researches and development; design of new machines, equipment and technologies; development efforts, the acquisition of patents or licenses, software products; education and training [9]. A whole range of technological solutions is needed to most effectively implement the priority areas.

Information technologies are such innovative technologies that can make the greatest contribution to accelerating economic growth and increasing the competitiveness of products. They are realized through computer design, an electronic archive, which contains all the information and from where it goes to the technologists, designers, and from them - to the design objects. At the same time, a large number of shortcomings in the organization of national production are revealed and there is an opportunity for their elimination [8].

At present, one of the main ideas for the development of industry should be neo-industrialization, which is a process of large-scale modernization based on waste-free technologies of automated, computerized, and robotic production [1].

The listed factors make it possible to define the main reference direction of the strategy for the further development of the foundry. These areas covered almost the entire range of problems of modern industrial production, namely:

- the maintenance and development directions of the world and national foundry production;
- modern technologies, materials, and equipment;
- diagnostics, certification and quality management of castings;
- computer technologies in the foundry.

As seen from the above, one of the main strategic tendencies of the foundry at the present stage is the development of simulation and computer technologies.

Mathematical simulation of casting processes is the most effective, reliable, and widespread method of manufacturing casting technology development in the world, which allows reducing the costs of both process engineering and production of castings.

Computer analysis at the stage of virtual design of the casting technology (before the manufacture of castings) allows: to minimize possible miscalculations and errors that inevitably arise in the development process; to reduce financial and time costs; to increase efficiency, competitiveness, quality, and reliability of products being developed. There is a saving of materials, energy carriers, operating time, equipment is saved, and in return, a lot of unique information about the technological process is obtained. Only computer simulation of the technology allows to look inside the product and see the nature of the processes taking place in it, and understand the causes of defects.

The introduction of computer technologies also makes it possible to increase the efficiency of operations for creating and processing information - there is a real transition from paper to electronic document flow. At the same time, costs, the labor intensity of designing and mastering the production of new complex products are reduced. For example, the costs of preparing technical documentation are reduced by 30...40% and the lead time of the release of new complex products is reduced by more than 35% [1].

The development of simulation and computer technologies in foundry production involves:

– automated design of foundry technology;
– modeling the cast molding - a synthesis system for all elements of the process;
– design of foundry technology and tooling in a CAD system with its subsequent manufacture on CNC machines;
– development of a rapid prototyping system;
– computer control of technological equipment.

Computer programs for simulation the casting processes are designed to solve the following tasks:

– development of complex or essential casting technologies;
– determination of the parameters that are most important in influencing the quality and yield of suitable products;
– finding the causes of defects in already used technologies;
– determining the technology's resistance to changes in external parameters;
– searching for new technological solutions for obtaining complex castings.

The ability to correctly solve these problems acquires an important, and often decisive, competitive advantage. One of the reasons for this is that the use of computer modeling involves a high culture of design, modeling, and manufacturing.

Currently, dozens of different software products are used in the foundry production aimed at solving the problems facing the casting technologists. They differ in their characteristics, use various computational methods, mathematical algorithms and physical models, which, to varying degrees, satisfy the needs of a particular consumer. Only a comparison of the results of computer simulation with the results of industrial and experimental researches allows assessing the objectivity and adequacy of the software product used.

2. Review of the most well-known systems for computer simulation of foundry processes

Today in the world there are a large number of programs for computer simulation of foundry processes. In world practice, the programs presented in Table 1 have received the main distribution.

Currently, in the USA, England, and Europe, the most common are two modeling systems: ProCast and MagmaSoft. In addition, a certain market segment in Europe is occupied by WinCast, SolidCast, and Nova-Solid/Flow systems. In Eastern Europe and the countries of the former CIS, the most popular software systems are Polygon and LVMFlow.

Modern programs for casting processes simulation are based on physical theories of thermal, diffusion, hydrodynamic, and deformation phenomena. They can adequately simulate many processes occurring during the filling of a mold with liquid metal, crystallization of a multi-component alloy, and further cooling of the casting. Possibilities of the programs include hydrodynamic calculation of filling molds, analysis of temperature fields during crystallization and formation of shrinkage defects, calculation of stresses and residual deformations in castings, optimization of gating systems.

Table 1 - Casting simulation software [5]

Country-Vendor	Casting Simulation Software	Country-Vendor	Casting Simulation Software
Australia	CastFlow	Japan	JSCAST
	Castherm	Korea	AnyCasting
China	InteCast	Russia	Polygon
Finland	CastCAE		LVMFlow
France	ProCast		FlowVision
	QuikCast	Spain	Vulcan
	PAM-Cast	Sweden	Nova-Solid/Flow
	CalcoSo	USA	PowerCast
Germany	MagmaSoft		SolidCast
	WinCast		CAPCast
Great Britain	MavisFlow		Flow3DCast
India	AutoCast		RAPIDCast

All programs mainly differ in purpose (Table 2), functionality, the number of simulated technological operations, the degree of completeness of the factors taken into account in the simulation, the equipment used. The main problems when choosing a specific program for modeling casting technological processes are the lack of reliable information about the capabilities of the program itself, the principles of working with it, as well as the absence of highly qualified specialists. A significant factor for national enterprises when choosing a program for modeling foundry processes is its cost.

Table 2 – Casting processes simulated by selected software

Casting process	AutoCast	CAPCast	CastCAE	Flow3D Cast	Magma Soft	Nova-Solid/Flow	ProCast	SolidCast	Polygon
Sand casting	+	+	+	—	+	+	+	+	+
High pressure die casting	—	+	+	+	+	+	+	—	+
Low pressure die casting	—	+	+	—	+	+	+	+	+
Continuous casting	—	—	—	+	—	—	+	—	—
Gravity die casting	+	—	+	+	+	+	+	+	+
Investment casting	+	+	+	—	+	+	+	+	+
Lost foam casting	—	—	—	+	+	+	+	—	—
Centrifugal casting	—	—	—	+	+	+	+	—	+
Tilt pouring	—	—	—	+	+	+	+	—	+
Squeeze casting	—	+	—	+	—	—	+	—	—

The main distinguishing feature of software products is the used numerical method for solving problems of differential equations in simulation the cast molding (Table 3).

Table 3 – Numerical methods in selected casting simulation software

Solution method	AutoCast	CAPCast	CastCAE	Flow3D Cast	Magma Soft	Nova-Solid/Flow	ProCast	SolidCast	Polygon
Finite Element Method	—	—	—	—	—	—	+	—	+
Finite Difference Method	—	—	—	+	+	—	—	+	—
Finite Volume Method	—	—	+	+	—	—	—	—	—
Vector Finite Element Method	+	—	—	—	—	—	—	—	—

Finite Difference Method (FDM), used in programs such as Magmasoft, SolidCast, CastCAE, JSCAST, AnyCasting and others, allows you to quickly obtain the stress pattern of shrinkage defects in the designed casting and correct the casting technology in time [7]. It is based on differential equations, in which the differential operators are replaced by finite-difference relations of varying degrees of accuracy [6]. As a rule, they are built on orthogonal meshes, which makes it possible to factorize operators and reduce the solution of a multidimensional problem to a sequence of one-dimensional problems, which means much simplify and speed up the solution of the general system of equations. The disadvantages include the poor boundary approximation of complex areas, which is not too fundamental for the heat-conduction equations, but rather essential for the hydrodynamic equations.

To eliminate internal shrinkage in critical castings, such a method is not suitable, since the applied mathematical tool does not work well enough in the case of rangy castings when the wall thickness becomes comparable to the mesh spacing. This is because the splitting of the original geometric model occurs by imposing a rectangular mesh with a constant step, which leads to a sharp increase in the number of computational cells in the case of obtaining rangy castings of large overall dimensions [4].

The Finite Element Method (FEM) used in programs such as Polygon, WinCast, CAPCast, and others, allows maximum consideration of the casting geometry and reveals even minor defects. It is based on heat and mass transfer integral equations [6]. The solution region in which the equations are solved is divided into finite elements (most often - tetrahedrons), within which approximants of functions are constructed based on the system of basis functions defined on the element [7]. By projecting the integral equations onto these bases, we obtain a system of finite-difference equations. This system is much more complicated than the one adopted in FDM; its solution requires large memory resources and considerable time.

The advantage of FEM is a proper boundary approximation, the disadvantages include the need for a high-quality generator of finite elements; the complexity of equations, and impossibility of factorization [6]. The built-in generators of the mesh model give large errors in the programs. The problem is solved by using an external finite element mesh generator, which leads to an increase in the cost of purchased software, operating time, and also requires highly qualified personnel.

At first glance, FDM and FEM differ in the representation of geometry, in the FDM the geometry is represented by bricks (parallelepipeds), and the FEM uses a fairly smooth mesh of finite elements (tetrahedra) of arbitrary sizes and configuration. This difference is not always clearly visible, because the visualization does not necessarily show a distorted brick geometry on the computer screen. It is possible to visualize the different solution on smooth surface meshes of the original geometric models so that the bricks were not visible. However, it is not a question of the modeled casting configuration, but a significant difference in the basic postulates of these methods and, as a consequence, in the different reliability of the solution.

FEM has a fundamentally more complex and adequate mathematical apparatus and more accurately describes the processes occurring in the considered geometric model. When simulating foundry processes FDM and FEM can have significant differences in the adequacy of the solution. It should be noted that currently almost all universal modeling packages, such as ANSYS, Nastran, Patran, etc. have long ago waived the deprecated FDM and use only FEM. More advanced foundry packages, such as ProCast, WinCast, Polygon, have followed the same path. The fact is that FDM is not suitable for complex geometries in problems with a significant influence of boundary flows [2]. For casting conditions, this means that finite-difference methods can be adequately used for casting in disposable molds with low thermal conductivity when there is no jump in the simulated function (eg temperature) at the casting mold boundary.

For pressure die casting, especially for complex shaped geometries, FDM will always give a fundamental systematic inaccuracy that is absent in FEM [3]. In addition, FEM is a less resource-intensive and faster method. For the same geometries, both methods give the same solution, but the FEM, when requiring equal adequacy with FDM, always requires about an order of magnitude less computational resources and the calculation time will be several times less.

The use of FDM in the foundry processes simulation is now justified only for solving hydrodynamic problems during pouring, since the magnitudes and directions of the velocity vectors change with greater discreteness than can be described by a finite-element mesh without losing the advantages of FEM in terms of calculation speed.

In software packages such as ProCast, Flow3D Cast, and Polygon, all major foundry problems are solved base on FEM, and especially for hydrodynamic problems, either FDM or intermediate methods are used. Often, the visualization of the conditional-difference solution in such basic-element packages is performed on a finite-element mesh, which is faster and more convenient.

The disadvantage is that most FEM-based programs have a very complex user interface, which in combination with the lack of experience with software products of foundry technologists reduces the benefits of using any simulation program to zero.

The Finite Volume Method (FVM) used in Nova-Solid/Flow and CastCAE programs is an integrated circuit. In a sense, it is a development of FDM, although sometimes it is considered as some intermediate stage between FDM and FEM. This is probably not entirely true, although FVM takes into account arbitrarily oriented boundaries within the difference cell, but assumes orthogonal difference subdivision (sampling) into rectangular parallelepipeds and has several other features inherent in FDM. FVM is a convenient method for using integral formulations when considering boundary conditions, it allows to control of mesh elements at the casting-mold boundary and simulate the processes of pouring and solidification of casting. FVM successfully solves filling problems, where the use of FEM is difficult, and FDM does not give the necessary conformity in the geometry of the filled cavity.

The software products Flow3DCast and LVMFlow also use FVM, which combines the simplicity and factorization of FDM, as well as a good approximation of the boundaries between different materials and phases It allows simulations to be carried out as quickly as possible without losing the accuracy of the calculations and provides reliable results even with coarse meshes. In any case, FVM has not yet become widespread for modeling casting processes, this is probably due precisely to the intermediate nature of the method. In those cases when arbitrarily oriented boundaries are required, it is better to use FEM itself, and when it is permissible to represent the geometry by a set of parallelepipeds, it is easier to solve the problem with classical FDM.

The Vector Element Method (VEM) used in the AutoCast program is based on determining the greatest thermal gradient at any point inside the casting, which is set by the vector sum of the flux vectors in all directions from this point [5]. The volume of the casting is divided into numerous pyramidal sectors from the considered point. Heat content and the surface area or cooling are calculated for each sector to determine the flux vector. The calculation is carried out in the direction of the resulting vector until the resulting one becomes zero. The feed line path is considered the curve along which the repetitions are done. It is possible to identify different hot spots in casting if the calculation starts with a plurality of starting points located in different areas of the casting.

VEM is relatively simple when compared to other numerical techniques but provides reliable and robust results [10]. Unlike FEM or FDM methods, VEM rectifies small errors while computing flux vectors at any point by automatically correcting them in subsequent repetitions. Moreover, VEM requires less memory and is also faster.

The boundary element method (BEM) is the most "strong" method since in its basic formulation it assumes within the boundary element the approximation of the distribution of the desired excosecant (for example, the temperature excosecant) directly according to the original differential equation, which describes the simulated process. In addition, when using BEM, spatial ordering occurs, which theoretically speeds up the solution and reduces the requirements for computing resources. However, for modeling casting processes, BEM is practically not used, because, despite of its advantages, it requires uniformity of physical properties in the areas of large boundary elements. This does not correspond to the physics of most casting processes associated with a significant change in the process parameters in local arbitrary areas, for example, in the area of heat output during solidification.

Practice shows that the optimal approach is not to choose a single numerical method to simulate casting processes but to use a combination of different methods, which makes it possible to increase the speed, accuracy, and adequacy of the results obtained to experimental data.

3. Research results of the advanced features and disadvantages of computer systems for casting processes simulation

In the course of the research, the possibilities, advantages, and disadvantages of the most common computer programs for casting processes simulation were investigated. The comparative analysis results of the compatibility options of computer programs for casting processes simulation are presented in Table 4.

MagmaSoft – is a multifunctional specialized program that allows you to simulate a variety of casting processes. This is one of the first commercial foundry packages, actually demonstrating for the first time that complex casting processes can be broadly simulated at a sufficiently high level. Thermal, hydrodynamic, and deformation processes are solved by numerical methods in MagmaSoft. The problem of predicting macroporosity and cavities is also numerically solved, although the models used in this case are simplified and do not fully take into account the complex and dynamic nature of the structuring of alloys during solidification. Forecast of microporosity, structural, mechanical, and other characteristics of casting is carried out at the level of criterion analysis.

The advantage of MagmaSoft is the presence of a sufficiently large number of empirical criteria, which at the level of criteria analysis allow predicting various properties, including the structure and mechanical characteristics of castings. In addition, the program implicitly integrates into the system various superimposed coefficients for a variety of casting methods, alloys, and materials, which to some extent compensates for the simplification of models and algorithms.

MagmaSoft has a convenient generator of difference meshes. If the initial geometry of the castings is relatively simple or the task of exact adherence the ratios of different wall thicknesses and a sufficient number of finite-difference elements along the wall thickness is not posed, then the generation of the calculated difference geometric model does not present any particular difficulties.

The disadvantage of this system is that the criteria used are hidden and it is impossible to edit, customize and supplement them, which significantly reduces the possibility of their adequate application. The above is also true of the choice of initial conditions, which are closed to the user and are determined by the casting method. This approach is acceptable for typical, widely used technologies. However, the lack of information on the choice of production parameters laid down in the system leads to the fact that the calculation results are often conditional.

In general, MagmaSoft is a system focused on solving typical casting tasks, except for special casting methods and technologies for producing castings of complex geometry. The program has good accuracy of the results obtained and a rich set of parameters for the simulation. MagmaSoft's long experience with foundries around the world has earned it a reputation for being a simple, reliable, and accurate package.

ProCast computer system, unlike MagmaSoft, is an extensive set of complex and physically universal models for solving serious production problems in the foundry industry, which significantly increases the adequacy of calculations. This system simulates thermal, hydrodynamic, and deformation processes, as well as processes of structurization and crystallization.

The program is able to forecast the occurrence of deformations and residual stresses in the casting and can be used to analyze such processes as core making, centrifugal casting, cavityless casting, and continuous casting. An accurate description of the geometry, due to the applied FEM, allows the ProCast system to simulate the filling of a mold with supernatant liquid and obtain reliable information about the erosion of a sand mold, air pockets, oxides, and turbulent flow, material age, non-spillages, and cold junctions, flow length and, overflows over-pours.

ProCast provides a complete solution for the simulation of the continuous and semi-continuous casting of billets. The program can simulate the steady-state mode, the initial and final stages of the process. The inverse calculation module automatically calculates the parameters of a material or process based on temperatures measured at targeted points or at the predetermined times. Primary and secondary cooling can be determined by inverse calculation.

This computer system has its own finite element mesh generator, which can be successfully used for geometries of medium complexity. For complex geometry models, specialized external generators are commonly used, which are currently available on the market.

A large database of materials for foundry models comes with ProCast. Its content is constantly updated with reliable data, verified in the conditions of existing foundry production. It includes the unique thermodynamic database that allows the user (by entering the chemical composition of the alloy) to automatically obtain the temperature curves of the properties necessary for an accurate calculation of the casting process.

The main advantages of this package include the ability to take into account complex thermal boundary conditions and direction of solidification, complex rheology in deformation calculations, the ability to simulate complex processes and numerically calculate the structure in castings. To carry out numerical calculations of the structure in ProCast, it is necessary to select the correct crystallization model and its parameters.

The disadvantage of the program is a too low level of solving the shrinkage problem, as well as the high cost, but it is justified by the capabilities of the program.

Thus, ProCast can be recommended as a basic system for castings and technologies of any complexity, excluding those cases where it is required to simulate the formation of shrinkage defects, taking into account the real dynamic nature of the structuring of the two-phase zone and the pressure drop due to filtration flow in the two-phase zone during shrinkage. This package is effective when technologists need to solve deformation problems with complex rheology and structure in the casting.

WinCast is a software package for casting processes simulation capable of calculating metal pouring (hydrodynamic and thermal analysis), metal crystallization (location of heat units and shrinkage defects),the tension of a casting (forecasts technological and operational stresses), structure-forming processes, heat treatment, and welding. The basis of the modular system is made up of basic and additional modules for sequential or parallel passage of various stages of modeling, and the solution of problems can be carried out jointly, taking into account their cross-impact.

Compared to Procast, WinCast has a more convenient process for building a mesh models, not inferior in the accuracy of calculations. The advantages of this model are the following: more accurate approximation of complex surfaces; more accurate representation of thin walls and complex sections with fewer elements; the ability to carry out thermal, hydrodynamic, and strength analysis on one mesh; fewer heat units reduce the calculation time.

The accuracy of thermal calculations is ensured by the correct approximation of surfaces by finite elements and by taking into account the temperature dependence of the properties of alloys and auxiliary materials. The reliability of hydrodynamic and strength analyzes is guaranteed by the compatible calculation of temperature fields on the same finite element pentahedral mesh with a high level of regularity. Generation of an accurate finite element mesh for 3D geometry of any complexity, built in an external CAD system or using the program's tools, provides accurate engineering forecasts in a short time.

The advantage of WinCast is that the database, organized in text format, is easy to edit and supplement. It contains the properties of alloys and materials in the form of tabular function of temperature. Thanks to a flexible preprocessor, the program provides accurate geometry display and the availability of automatic mesh generation.

Among the disadvantages, it should be noted is an inconvenient interface, as well as the use of simplified models when solving the heat problem (solidification) and the shrinkage-filtration problem (the formation of micro-and macroporosity). The inability to automatically generate the computational grid requires additional spadework to create it. However, in WinCast, deformation processes are simulated at a sufficiently high level as a result of casting cooling.

SolidCast is an entry-level computer system that is designed to solve current production and technological problems, as well as to optimize the technology for each casting based on the geometry optimization of the gating-feeding system and the technological parameters of the casting process.

The computational capabilities of the package allow the user to trace the dynamics of filling the mold with metal and the crystallization process of the casting in the mold; to obtain information about the time of crystallization, the rate of cooling, shrinkage defects; to determine the possible areas of defect occurrences in the casting. The built-in hydrodynamic module allows you to simulate the flow of the melt in the mold, as a result of which it is possible to identify and forecast such defects as mold erosion, cast seams, surface contaminations, and misruns in the casting.

As a result of the calculation, the technologist receives information about the allocation of temperature fields in the casting and the mold, the values of the melt flow rate, and the pressure of the melt on the mold walls at any point.

SolidCast has a built-in mesh generator in two versions and an automatic generator of graphs and diagrams in the postprocessor, which allows comparing the simulation results of several variants of manufacturing technologies for the same casting. The availability in the SolidCast computer system of the possibility of automatic generation of the computational mesh permits optimizing the casting mold depending on scrap yield and the size of the flask. In addition, this software product allows to creation of a unique database on the used technological processes for casting production. The built-in database of molding materials and alloys is open to the user, it is constantly changing and supplemented.

The disadvantages of SolidCast are as follows: inconvenient interface, inability to take into account preliminary mold filling; inconvenient display of calculation results for visual analysis; excessive duration of computer calculations. Extensive functionality and unique pricing policy of developers make SolidCast the best in terms of price-functionalities-productivity since one acquired licensed program can be used at five workplaces within one enterprise.

Table 4 – Comparative analysis of the compatibility options of computer programs for casting processes simulation

Functionalities		MagmaSoft	ProCast	WinCast	SolidCast	Nova-Solid/Flow	Polygon
1	2	3	4	5	6	7	8
Problem definition	databases of additional technological elements	+	—	+	+	+	+
	addition and editing of databases	+	+	+	+	+	+
	applying filters	+	—	—	—	+	—
	modeling of gating bowls and separately filled gating systems	+	—	—	—	—	—
	boundary conditions correction	+	+ (except for the internal casting elements)	+	+	+	+
	simulation of filling the stopper and teapot ladles	+	+	—	—	—	—
	calculation of the sector of 1/p part of an axisymmetric casting	+	+	+		—	+
Mold filling calculation	basic hydrodynamic equation	Navier–Stokes	Navier–Stokes	Bernoulli		Navier–Stokes	3DFlow
	analysis of temperature fields during filling	+	+	—	+	+	—
	mold erosion analysis	+	—	—	—	—	—
	filling analysis (tracers of particulate movement in time, speed, and distance)	+	—	—	—	—	—
	accountancy of the effect of mold gastightness	+	—	—	—	—	—
	accountancy of the influence of the gas-generating abilities of mold and cores with binders	+	—	—	—	—	—
Calculation of solidification	used mathematical apparatus	Fourier	Fourier	Fourier	Fourier	Fourier	Fourier
	temperature field analysis	+	+	+	+	+	+
	calculation of solidification tracers	+	—	—	—	—	—
	calculation of thermal convection vectors	+	—	—	—	—	—
	alloy segregation calculation	+	+	—	—	—	—
	oriented crystallization analysis	+	+	—	+	+	—
	orientation analysis of direct-grown crystals	+	—	—-	—	—	—
Calculation of stresses	stress analysis	+	+	+	+	—	—
	analysis of casting and mold deformations	+	+	+	+	—	—
	analysis of stress-forming rate in the casting during solidification	+	—	—-	—	—	—
	calculation of hot and cold crackings during crystallization	+	+	—-	—	—	—
	calculation of hot and cold crackings after completion of the crystallization process	+	+	+	+	—	—
Heat treatment	calculation of the heat treatment process of the casting	+	—	—	—	—	—
	calculation of the heat treatment process of the casting after premachining	+	—	—	—	—	—

End of Table 4

1	2	3	4	5	6	7	8
Integration feasibility	admissibility to web deploy of custom applications and macros	+	—	—	—	—	—
	admissibility to export calculated data for sequent analysis in other CAE systems	+	+	—	—	—	—
Automatic calculation	optimization of casting technology parameters	+	+	—	—	—	—
Defects analyzed	micro flaws	+	+	+	+	—	—
	macro flaws	+	+	+	+	+	+
	gas unsoundness of casting	+	+	—	+	—	—
	erosion of mold and surface contaminations of casting	+	—	—	—	—	—
	cold and hot crackings in the solidificating process	+	+	—	—	—	—
	cold and hot crackings after solidification	+	+	+	+	+	+
	non-fills	+	+	—	+	+	—
	veining	+	—	—		—	—
Alloy casting analysis	steel	+	+	+*	+*	+*	+*
	cast iron	+	+	+*	+*	+*	+*
	aluminum alloys	+	+	+*	+*	+*	+*
	magnesium alloys	+	—	—	—	—	—
	zinc alloys	+	+	+	+	+	+
	titanium alloys	+	+	—	+	—	+
	copper alloys (bronze, brass)	+	+	+	+	+	+
	alloys with non-Newton' flow rheology	+	—	—	—	—	—
Analysis of casting methods	sand casting	+	+	+		+	+
	oblique casting	+	—	—	—	—	—
	permanent-mold casting	+	+	+	+	+	+
	investment casting	+	+	+	+	+	+
	cavityless casting	+	—	—	—	—	—
	high pressure die casting	+	+	+	+	+	+
	injection molding	+	+	—	—	—	—
	low pressure die casting	+	+	+	+	+	+
	centrifugal casting	+	+	—	+	—	—
	over-pressure casting	+	+	+	+	+	+

*without calculating the microstructure

The Polygon computer system is designed to simulate hydrodynamic, thermal, and shrinkage-filtration processes during casting. In addition, the problem of reticulation of electric potentials during solidification of casting in the electric fields is solved by numerical methods. Criteria analysis methods allow predicting strength, hardness, structural parameters, and erosion of forms.

When using the Polygon software, simulation is carried out based on the finite element method, which allows using the most adequate physical and geometric models. All models and functions are implemented for 3D geometric models. Solvers can use not only direct but also iterative calculation methods. This makes it possible to significantly reduce the calculation time and the required random access memory, which in combination with the finite element method, calculaties castings of any complexity available on a personal computer.

Based on the criterion analysis, the Polygon system package contains a special module that allows using not only the criteria proposed by the developers for predicting mechanical properties, but also to form a base of own complex criteria, taking into account the chemical composition and the logic of transition from one formula to another.

This enables the user to adequately forecast various technological and operational properties of the casting.

The possibility of taking into account complex boundary conditions for castings of complex geometry when using special casting methods makes it possible to use the Polygon computer program in complex foundries, in particular, by methods of directional solidification. One of the most important properties of Polygon is adequate and modern physical models of the shrinking process. It carries out a combined calculation of the formation of shrinkage micro and macro defects by two completely different mechanisms with the calculation of the filtration flow, pressure fields in the casting, and complex dynamic changes in the structuredness of the alloy in the solidification interval. The problem of shrinking the defects in numerical solutions in other casting packages is not solved.

When choosing the properties of alloys, materials, boundary, and other conditions, the user has full access to all parameters, also can change and supplement the initial databases by properties in any way.

The disadvantages of the package include the absence of a full-scale deformation task taking into account complex rheology and the excessive complexity of models when solving hydrodynamic problems, namely: an extremely inconvenient interface; the complexity of preparing mesh model, the complexity of data entry, an insufficient database of materials and alloys, as well as the need for purchasing additional software for generating the mesh model.

Thus, Polygon is a modeling system designed to solve the problems of casting technology simulation for any casting method with unlimited complexity of the casting geometry, taking into account the maximum number of operating factors. The advantages of the package, in addition to the use of finite elements, include complex and adequate physical models of thermal processes, the ability to take into account complex boundary conditions, and displacement of objects (for directional casting solidification, as well as a comprehensive problem solving of shrinking. Practice shows that for essential castings, the Polygon program can be used in combination with other packages for foundry processes simulation as testing tools for developing the optimal technology for producing castings.

Conclusions

This study presents a comparative analysis of the most well-known computer systems for casting simulation in terms of their functionalities for modeling hydrodynamic, deformation, filtration, crystallization, and other processes, following metallurgical and foundry technologies.

The analysis shows that at present it is impossible to offer a computer system that can satisfy both plant technologists and research engineers. When choosing a specific computer system or package, the user should proceed from his financial capabilities related to its cost, as well as from the volume of those tasks that need to be solved using modern simulating tools. Experience shows that the results of such studies are in great demand both by research scientists and by foundry specialists and managers.

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