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ANALYSIS OF TECHNOLOGICAL DAMAGEABILITY OF CASTINGS MANUFACTURED IN SAND MOLDS

За результатами розсіювання характеристик твердості встановлено, що технологічна пошкоджуваність окремих об'ємів виливка залежить від розподілу температурних полів, напрямку тепловідведення, особливостей живлення рідкою фазою металу, що кристалізується. Збільшення віддалі від живильників сприяє підвищенню, а прискорене охолодженння та спрямоване тепловідведення зменшенню технологічної пошкоджуваності виливка при затвердіванні.

Ключові слова: *технологічна пошкоджуваність, коефіцієнт гомогенності Вейбулла, прискорена кристалізація, рідка фаза, ливарні дефекти.*

1. Introduction

In the conditions of market relations, the competitiveness of products, which is determined not only by qualitative and economic indicators, but also by reliability characteristics, is of paramount importance. Reliability characteristics are laid when designing products, they are provided during their manufacture, but they are manifested only during the operation of parts and machines [1–6].

Modern machine building, actively developing in the direction of creating automated systems for obtaining parts, finished products, requires the use of new or traditional materials with an increased set of structural and functional characteristics. Strength and reliability of complex technical products depends on a set of factors associated with the properties of materials, geometric parameters of structures and technologies for their production.

The absence of methods for transferring data characterizing the properties of materials to their behavior in loaded structures in the practice of their calculations is replaced by insufficiently substantiated safety factors. The development of information support for machine building makes it possible to obtain high-tech products using flexible technologies at minimal cost. This approach is based on the use of multifunctional computer systems, which are consistently perform volumetric product design (CAD), the design basis for its reliability and availability (CAE), preparation of manufacturing processes (CAM) and product data management (PDM).

CAE computer-aided engineering analysis software allows to formulate the new approaches to the selection of materials and the improvement of processing technologies to improve the operational durability of products based on the calculated justification. It should be noted that the use of these programs is limited to the lack of established interrelationships of technological heredity with the life cycle of parts and machines, so research in this direction is relevant.

2. The object of research and its technological audit

The object of research is the technological damageability of castings made from aluminum alloy ВКЖЛС-2, obtained in sand molds. Castings made from the investigated alloy are used for the manufacture of parts, in particular pistons of internal combustion engines, operating under alternating loads, contact interaction and wear. As a result of structural heredity, damages resulting from casting conditions can develop during subsequent machining and operation of products.

In the problem of general analysis of materials, technologies and structures, heterogeneity of the structure is of considerable interest that are formed during the crystallization of alloys, depending on the conditions of heat removal. Elements of such structure are primary grains, their boundaries, caverns, formation and properties of which depend on the liquation of the components of the alloys and the features of their crystallization. In the design of parts, the design strength calculation is carried out from the standpoint of the mechanics of continuous media without taking into account the technological defectiveness of the metallic material and the uneven distribution of properties in macrovolumes.

At the same time, heterogeneity of physicochemical and technological origin influences the structural strength of parts and products, but its influence is not fully understood. Forecasting of the reliability of parts and machines based on the introduction of PLM-concepts requires experimental research and theoretical analysis of the effect of the properties of local volumes of structural materials on their behavior during technological processing and operation.

3. The aim and objectives of research

The aim of research is to determine the technological damageability of the various zones of castings made from aluminum alloys obtained by casting into sand molds.

To achieve this aim, the following tasks are accomplished:

1. Conducting analysis of modern concepts of assessing the damageability of metallic materials.
2. Planning and implementation of microstructural studies and technological damageability of various zones of cast billets.

4. Research of existing solutions of the problem

The priority task in the design of rational technological processes for the manufacture of machine parts is the

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interaction (alignment) of their qualitative and quantitative indicators with the provision of high process productivity and the maximum possible loading of technological equipment [2].

Dependence of the operational properties of products on their quality indicators is complex for the following reasons [7, 8]:

1) the process of disability, having a certain physical nature, is subject to the laws of random functions through the variability of operating conditions and the instability of the technological process;

2) through the complexity of most technological processes and emerging side effects it is difficult to identify all those process parameters that really affect the operational properties of products.

Researches [8] found that the inadequate quality of the development of the concept of the product and the preparation of its production accounts for 80 % of all defects in production and use of products. The refusal during the warranty period of machine parts is affected in 60 % of cases directly related to erroneous, unfinished developments and non-compliance with technical requirements.

Therefore, ISO 9001:2008 standard emphasizes the integration of all actions (operations). At the same time, the center of gravity of works is transferred from functions to a process that ensures the unity of management, the improvement of the organizational culture and allows PLM technologies to be effectively implemented [9].

Heredity plays an important role in assurance of quality indicators (Fig. 1) – the transfer of properties of the processed object (billet) from the previous design stages to subsequent that affected the performance characteristics of the final product [9, 10].

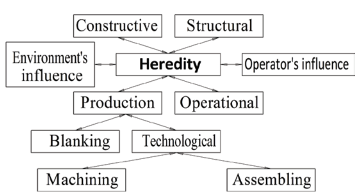

Fig. 1. Types of heredity in the life cycles of the machine [6]

However, when analyzing the influence of technological heredity on the quality parameters of the final product, the role of blanking operations is not sufficiently taken into account [3, 9]. Researches [11] found that the structure and properties of blanks are closely related to the heredity of the metal in the liquid state. Only 25 % of the properties of the charge are transferred to the billet, and 75 % is formed during the pouring and curing of the alloy upon cooling.

Thanks to the success of the theory and practice of foundry production, in particular, the achievement of foundry metallurgy, cast billets are widely used in the engineering industry instead of deformed ones.

A fundamentally important feature of foundry alloys in comparison with deformed ones is their ability to provide high characteristics of the mechanical properties of cast metal without the use of plastic deformation, on which a high level of strength and plasticity depends upon deformation. This is due to the fact that during plastic deformation there are significant qualitative changes in the cast structure. In particular, primary grains are broken and ground, nonmetallic inclusions in the grain volume, as well as non-metallic layers at the boundaries of primary grains, porosity is eliminated and chemical heterogeneity is reduced.

In the absence of plastic deformation of castings, their behavior during technological processing and operation is determined by the structure that is deformed after the primary crystallization and complete curing of the metal.

The development of modern machine building is characterized by an increasing role of providing project stages with information about the properties and behavior of materials under certain technological regimes for their processing and operation. This requires the development of methods for computer modeling of the structure, properties and processing of materials, as well as interpreting the transferring into CAE computer models. It should be noted that the relationship between the factors influencing the quality of products and their behavior during operation at the level of mathematical models is not fully developed, which makes computer designing difficult [12, 13].

At all stages of designing and preparing production of engineering products in integrated CAD/CAE/CAM/PLM environments, there is a need to take into account and analyze the behavior of materials [14], questions are raised about the joint design of materials and engineering products [15, 16]. Modern methods of modeling foundry technologies allow to accurately calculate the temperature fields and predict shrinkage defects in castings. But existing software can't reliably determine the fracture zones in foundry alloys, taking into account the factors affecting the nucleation and development of cracks. In this case, experimental and theoretical developments are necessary to refine mathematical models and develop such computer programs.

High-temperature defects are formed upon cooling of the alloys as a result of a stepwise increase in the density of the metal during the phase transition from the liquid to the solid state. At the final stage of solidification, with the approach to solidus temperature, when a certain amount of solid is reached, a rigid frame with isolated volumes of the liquid phase appears.

The stretching of the liquid phase within the two-phase zone increases with the growth of the solid phase that facilitates the filtration of the melt into the interdendritic space. When liquid access ceases, conditions are created for the formation of micropores and release of gases into them. With the formation of a rigid framework, foundry shrinkage begins. From the beginning of shrinkage to solidus temperature, there is an effective crystallization interval in which shrinkage defects are formed in the form of caverns, micropores and crystallization cracks. Such defects are an integral part of the heterogeneous structure of casting alloys. They have a significant impact on the lifetime of cast parts that is reflected in calculations of reliability and serviceability of products.

When manufacturing machine parts, it should be borne in mind that the structure of materials is formed under the influence of technological processes in non-identical conditions for individual microbes and regions. This leads to a spatial heterogeneity of the structure and fields of physical and mechanical properties at all dimensional levels from macro to microscopic. To optimize technological processes and increase the operational reliability of casting materials, it is necessary to establish a connection between their heterogeneous structure and mechanical properties, to give a quantitative estimate of the strength effectiveness of the finished part macrovolumes.

The effective strength of the heterogeneously structured material reflects the minimal destructive load and is limited by the local strength of non-weakened microbes. Micropores and microcracks appearing in the alloys during crystallization can reduce the strength of cast billets and initiate fractures when the subsequent processing of billets or the operation of finished products after casting.

An important role in the machining of parts is played by constructive heredity. It should be taken into account in the development of technological processes, as well as at the stage of designing high-precision parts. This allows to predict and control the shape error and the relative position of the surfaces of the products [13].

Already at blanking operations, in particular with mechanical and thermal treatments, structure defects are formed, which during the operation of the structure begin to develop intensively, causing dangerous damage in the form of pores and microcracks. The development of the theory of accumulation of scattered damages (defects) makes it possible to analyze the causes of deterioration in the characteristics of the physical and mechanical properties of the products.

Formation of technological damages in blanking operations, in particular foundries, their development during machining and operation and the change in reliability of parts and machines under these conditions have not been adequately studied.

5. Methods of research

The local nature of the formation of defects and cracks in casting conditions necessitates a study of the process of accumulation of damages and formation of cracks in materials in the preparation of castings.

The multistage process of metal disintegration contains the following stages [17–20]:

1) accumulation of damage and disruption of the continuity of the material in the stress and strain field;

2) development of microcracks in a medium with defects;

3) growth of cracks and separation of material with loads and movements set at the boundaries of the billet.

Damageability W in most studies of the causes of material destruction during operation is not associated with the structure. Only with the use of energy approaches to describe the processes of accumulation of damage [21, 22], it is considered that as a result of viscoplastic deformation, two types of microdamages develop – along the body and along the grain boundaries. Internal variables that determine the processes of damage accumulation are scalar parameters – the energy of damageability along the grain body W_p and the energy of damage along the grain boundaries W_n:

$$W_k = \int_0^t w_k,\ k = p, n. \quad (1)$$

The damageability W_k depends on the history of viscoplastic deformation of the material. Damageability along the body and along the grain boundaries is characterized by the relative damage parameters W_p and W_n, respectively.

$$0 \le W_p \le 1, \quad (2)$$

$$0 \le W_n \le 1. \quad (3)$$

Total damageability of the material W:

$$0 \le W \le 1. \quad (4)$$

Increase in damageability:

$$\Delta W = dW_n + dW_p, \quad (5)$$

where $dW_n = dW_n(T, W_n, W_p)$ and $dW_p = dW_p(T, W_n, W_p)$.

Total increase in damageability:

$$\Delta W = dW_n + dW_p, \quad (6)$$

$$\Delta W_n = \Delta W_{nR} + \Delta W_{n\delta}, \quad (7)$$

$$\Delta W_p = \Delta W_{pR} + \Delta W_{p\delta}, \quad (8)$$

where ΔW_{nR}, $\Delta W_{n\delta}$ – the increment of grain-boundary damageability, respectively, due to viscoplastic deformation and as a result of changes in the conditions of deformation; ΔW_{pR}, $\Delta W_{p\delta}$ – the increment of intragranular damageability, respectively, due to viscoplastic deformation and as a result of a change in the form of the stressed state and temperature.

To determine the damageability degree of the material W, during the operating time, direct (methods of metallography, weighing) and side (acoustic emission, electric resistance) methods of measuring the mechanical properties of metal without destruction are used. Their application leads to large errors, since the relationship between the measured parameters and the characteristics of the structural state for a wide class of materials is ambiguous.

Analysis and assessment of the physical heterogeneity of the structure, damageability of various zones of cast billets are carried out using the LM-hardness method. According to this method, the dispersion degree of the characteristics of the mechanical properties of the material after operating at different stress levels is taken as the parameter of damage. Scattering of measurement results made by identical instruments under identical conditions is more representative of the correlation between the mechanical properties of the material characteristic and the state of the structure than the absolute values of the characteristics. This method is easier to implement, using as a mechanical characteristic the hardness, the value of which is used for indirect evaluation of properties [21, 22].

Parameter that integrally characterizes the state of the material when processing the results of hardness measurements is homogeneity, which is estimated by the Weibull coefficient (m). A large value of the coefficient m corresponds to a low level of dispersion of the hardness characteristics and a low damageability degree; for the lower value, on the contrary, the damageability degree is higher [21, 22].

The Weibull homogeneity coefficient (m) is calculated by the formula [21]:

$$m = \frac{d(n)}{2{,}30259 \cdot S(\ell g(H))}, \quad (9)$$

where $d(n)$ – a parameter that is determined by the number of measurements, n;

$$S(\ell g(H)) = \sqrt{\frac{1}{n-1}\cdot\sum_{i=1}^{n}\left(\ell g(H_i) - \overline{\ell g(H)}\right)^2}, \quad (10)$$

$$\overline{\ell g(H)} = \frac{1}{n}\cdot\sum_{i=1}^{n}\ell g(H_i). \quad (11)$$

The effect of the material structure on its damageability W is also investigated in the article. It is estimated by the formula:

$$W = \frac{m_{\max} - m_i}{m_{\max}}, \quad (12)$$

where m_i – the value of the Weibull coefficient on the i-th measurement line (plane); $M_{\max}$ – the maximum value of the Weibull coefficient for a series of measurements.

6. Research results

For experimental studies, the billets are cast in a sand mold with dimensions of 165x155x20 mm made from the material АК21М2.5Н2.5 (ВКЖЛС-2) GOST 1853-93. A sample of 155x20x20 mm is cut from the billet and the base surface is milled using the 6Р12 vertical milling machine with an end milling cutter ∅30 mm (cutting modes: $t=2$ mm, $S=270$ mm/min, $n=300$ min^{-1}).

On two surfaces opposite the base, preparations for microstructural studies are carried out according to the standard procedure described in [17, 18].

After that, the hardness is measured in sections parallel to the base plane from both sides (casting edge and inner side) on the ТР-5006 (Russia) using a ball ∅3.175 mm at a load of 588.4*N*. The billet after the hardness measurement is shown in Fig. 2.

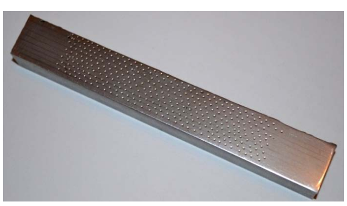

Fig. 2. Billet after hardness measurements on the device ТР-5006 (Russia)

Based on the results of the study, the Weibull homogeneity coefficient (m) is calculated from the formula (9) and the damage of the casting material W by formula (12) in the Mathcad 15 environment. According to the obtained data, the curves of the dependence $m=f(h)$ and $W=f(h)$ are built (Fig. 3, 4).

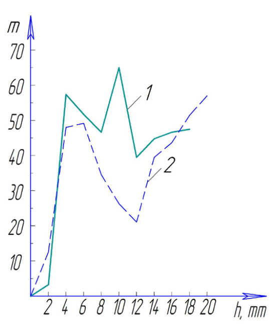

Fig. 3. Dependence graph of the homogeneity coefficient (m) on the depth of measurement for the billet sides: 1 – internal; 2 – external

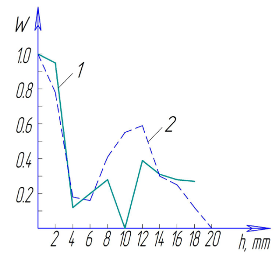

Fig. 4. Dependence graph of material damageability W on the depth of measurement for the billet sides: 1 – internal; 2 – external

After that, intensity (density) of surface defects is studied for the inner side of the billet using an electron microscope (magnification 15 times) (Fig. 5–8). Based on the results of the studies, the dependences $N=f(d)$ are plotted (N, d are the number and size of structure defects, respectively), which are shown in Fig. 9.

Applying the grid with a 10 mm step on the photo of material structure in the zones I–IV, the relative porosity (defectiveness) of the structure P, %, is calculated according to the formula:

$$P = \frac{L_{def.}}{L_{tot}}, \quad (13)$$

where L_{def} – the total length of grid lines with defects; L_{tot} – the total length of the grid lines.

The plot of $P=f(h)$ for the inner side of the casting is shown in Fig. 10.

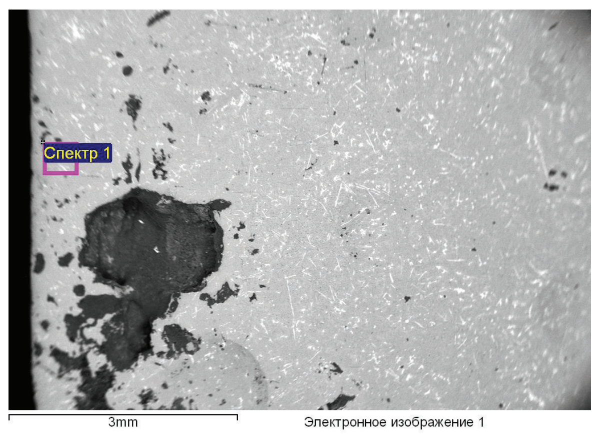

Fig. 5. Structure in the zone I from the casting surface

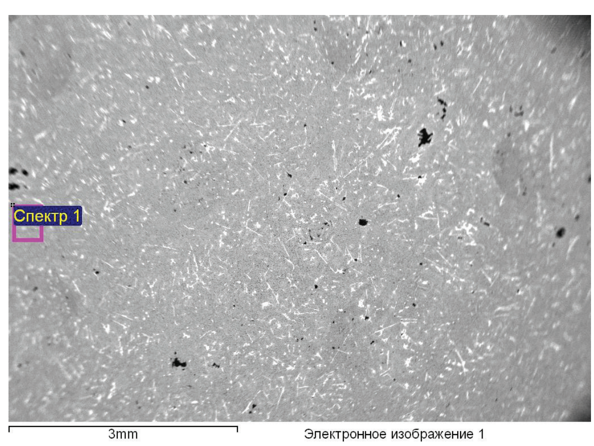

Fig. 6. Structure in the zone II from the casting surface

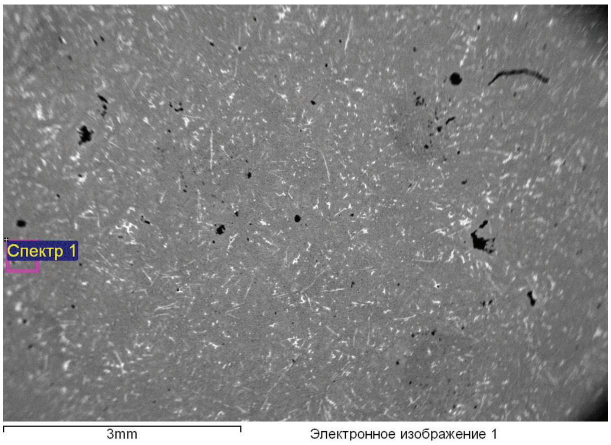

Fig. 7. Structure in the zone III from the casting surface

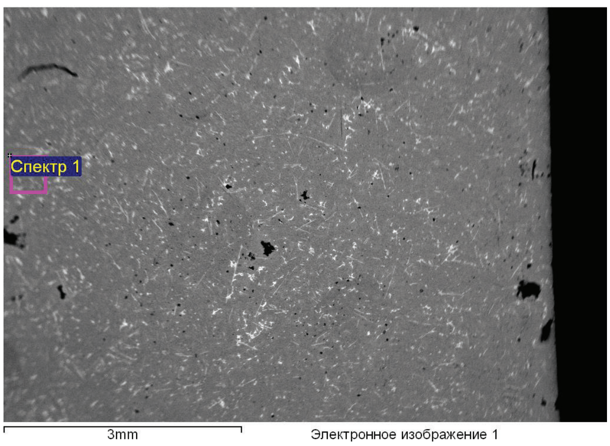

Fig. 8. Structure in the zone IV from the casting surface

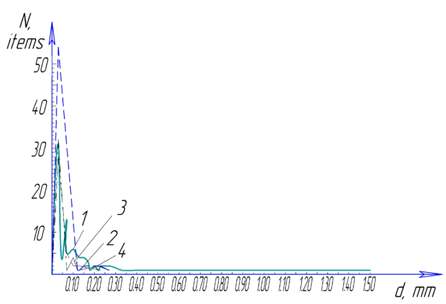

Fig. 9. Dependence of the number of defects *N* on their dimensions *d* for zones from the casting surface: 1 – I; 2 – II; 3 – III; 4 – IV

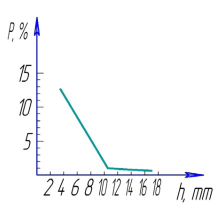

Fig. 10. Dependence of the relative porosity (defectiveness) of the structure *P* of the test sample

The obtained results show that the greatest amount of technological damage in the cast billet is formed at a depth of 2 mm from the surface that is crystallized last (zone I). This is due to the specifics of the curing process of the metal, the presence of impurities and inhomogeneities in the surface layer, and is confirmed by the small values of the Weibull homogeneity coefficient (*m*) (Fig. 3), and by the large damageability values *W* (Fig. 4).

With the further movement of the material deep into the material (from 2 to 4 mm) in the zone I, a decrease in the damageability is observed, as well as its stabilization for the inner side and its relative oscillations for the outer side of the billet. This is due to the conditions of the crystallization process of the casting. At a distance of 4–6 mm, the damage is significantly reduced. The difference in damageability for the inner and outer sides of the billet at a distance of 10 mm from the surface (Fig. 4) is due to the fact that the inner side is 40 mm from the feeder and the outer side at a distance of 60 mm. That is, during crystallization, the inner side of the billet is better fed with liquid metal than the outer one. The growth of damage at a distance of 12 mm from the casting surface is due to the fact that this zone is in the center of the casting, where the microstructure of the primary crystals is disoriented in all directions as a result of the heat removing. Damageability is less in the zones of formation of directed crystallites.

Technological defects are present in all investigated areas of the material (Fig. 5–9). However, if the pore size does not exceed 0.22 mm in the zone II, 0.27 mm in zones III–IV, then in the zone I there are single pores with a size of 1.5 mm. The relative defectiveness of the structure P also indicates a greater number of casting damages, which is almost 10 times larger in the zone II than in the other zones (Fig. 10).

Spectral analysis shows an increase in oxygen content and a decrease in aluminum in the upper part of the cast (zone I) as compared to the lower part (zone IV) (Fig. 5, 8, Table 1).

Table 1

The content of elements in zones I, IV of the test casting

The content of chemical elements in the zone I			The content of chemical elements in the zone IV		
Element	Weight	Atomic	Element	Weight	Atomic
O K	8.46	13.70	O K	6.12	10.21
Al K	69.73	66.96	Al K	69.79	69.04
Si K	20.28	18.71	Si K	19.86	18.87

The distribution of other elements in all zones is generally uniform.

7. SWOT analysis of research results

Strengths. It is proposed to use the LM hardness method to assess the damage of castings, since an irregular structure is formed in the preparation of billets and defects are formed. This method is developed at the Frantsevich Institute of Problems of Materials Science (Kyiv, Ukraine) [21, 22] for the study of deformed materials. The LM hardness method will make it possible to quantitatively determine the technological damages of castings depending on the features of the designs of the molds, heat removal, preparation of melts, and the conditions for their casting into molds. The quantitative assessment of damageability also makes it possible to select economically feasible technological solutions to improve the longevity of products.

Weaknesses. The weakness of the LM hardness method is the necessary to cut out samples from individual casting volumes, the damageability of which must be investigated.

Opportunities. The introduction of the LM hardness method at the enterprises of the machine-building profile will allow reducing the time for the design and technological preparation of the production with the introduction of casting technologies, and will contribute to the development of information support of machine building in Ukraine. Further research in this direction should be directed to the establishment of direct links between certain reliability indicators, which integrally describe the damageability of the material W and the technological parameters of the blanking operations of machining.

Threats. The existing methods do not allow quantifying the damageability of cast materials, since the relationship between the measured parameters and the structural state is ambiguous. When the material is dissected by the indenter of the hardness tester, the delay can be evaluated for the ability of local areas whose damageability is different. Therefore, it is necessary to develop the LM hardness method for computer research of phenomena affecting the reliability and conditions of destruction of cast billets during their preparation and processing.

8. Conclusions

1. Based on the analysis of modern concepts of the damageability assessment of metallic materials, it is shown that it is expedient to evaluate the technological damageability of various zones of cast billets with complex spatial geometry that contain massive thermal assemblies and thin walls, according to the dispersion degree of the hardness characteristics. The technological damageability of the billets obtained in sand molds varies widely and mainly depends on the crystallization conditions of their individual volumes:

– distribution of temperature fields;
– direction of the heat removing;
– the features of the metal feeder with a liquid phase during crystallization.

The influence of the mold design on the formation of technological damage is analyzed. Increasing the distance from the feeder promotes growth, and accelerated crystallization and directed heat removing promote reduce in technological damage to the volume of the casting when cured.

2. Based on the planning and implementation of microstructural studies, it has been established that the damageability of the material *W* both at the blanking operation and at further machining operations serves as a parameter that quantitatively evaluates the product reliability characteristics, in particular, no-failure operation. In particular, the technological damageability is 1.3–6.5 times higher than for the base material in the near-surface layer at a depth of 2 mm.

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АНАЛИЗ ТЕХНОЛОГИЧЕСКОЙ ПОВРЕЖДАЕМОСТИ ОТЛИВОК, ИЗГОТОВЛЕННЫХ В ПЕСЧАНЫХ ФОРМАХ

С использованием результатов оценки рассеивания характеристик твердости установлено, что технологическая повреждаемость отдельных объемов отливки зависит от распределения температурных полей, направления теплоотвода, особенностей питания жидкой фазой кристаллизирующегося металла. Увеличение расстояния от питателей способствует

повышению, а ускоренное охлаждение и направленный теплоотвод уменьшению технологической повреждаемости объемов отливки при затвердевании.

Ключевые слова: технологическая повреждаемость, коэффициент гомогенности Вейбулла, ускоренная кристаллизация, жидкая фаза, литейные дефекты.

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DEVELOPMENT OF A SYSTEM FOR ORGANIZING A MODULAR DESIGN AND TECHNOLOGICAL PREPARATION FOR THE PRODUCTION OF CAST IRON PISTONS FOR INTERNAL COMBUSTION ENGINES

Запропоновано систему модульної конструкторсько-технологічної підготовки виробництва чавунних поршнів двигунів внутрішнього згоряння (ДВЗ). Особливістю даної системи є те, що вона забезпечує можливість одночасного виконання конструкторських, технологічних і організаційних робіт. Показано, що це досягається шляхом використання модульного принципу проектування чавунних поршнів ДВС. Для прикладу реалізації одного з модулів проведено моделювання напружено-деформованого стану монолітних чавунних поршнів.

Ключові слова: *модульна система, поршень ДВС, вермикулярний графіт, напружено-деформований стан, алюмінієвий ЧВГ.*

1. Introduction

When creating modern internal combustion engines (ICE) and improving the quality of existing ones, special attention is paid to the design and technological preparation of the production of their parts, primarily pistons, which from all engine parts work in the most difficult conditions. Pistons determine the reliability and life of the engine as a whole.

Advances in the production of castings of high-strength cast iron with globular and vermicular graphite in recent decades cause increased attention and interest in cast iron as a material for highly loaded parts of diesel internal combustion engines. In the late 80s of the last century, joint research of the departments of internal combustion engines and foundry of the National Technical University «Kharkiv Polytechnic Institute» (Ukraine) carried out research work on the use of cast iron for pistons of perspective diesel engines. As a result of these studies, thin-walled monolithic and composite pistons made from CGI are developed and manufactured.

Traditionally, these works are carried out consistently from the design of the piston to the design of its production technology. Currently, the design and manufacture of internal combustion engines is impossible without taking into account the technological aspects of manufacturing parts and engine components. This can provide a modern technical level of design and technological design of ICE and is the justification of the relevance of conducted research in this direction.

2. The object of research and its technological audit

The object of research is the process of design and technological preparation for the manufacture of ICE cast pistons. Characteristic feature of this object is the complexity of taking into account the interrelationships of individual design elements and the technology of cast ICE pistons production. To identify these relationships, a technological audit of the standard design process is carried out using expert assessments, aimed at identifying the significant factors that determine the bottlenecks in the design system. The rationale for this approach is that in fact there is no uniform opinion on the priority of an element in the design. The design part, based on the use of fundamental design principles from the field of resistance of materials, dynamics and strength of machines, heat transfer, etc. does not take into account the features of the manufacturing technology. In this case, as practice

