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Cast Irons with Special Properties

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Abstract. There are presented the results of studies carried out in the field of developing cast iron with special properties and technologies of their production: cast iron with increased structural strength, aluminum and austenitic-bainitic cast iron.

Key words: results, studies, cast iron, aluminum alloys, special properties, production technology, structural strength, aluminum and austenitic-bainitic cast irons.

Introduction

The reasons for the formation of defects in castings, as well as methods for their prevention, have always been the focus of attention of foundry specialists. A wide variety of defects makes it difficult to establish the mechanism of their formation, so there are various explanations for the occurrence of defects.

The complexity of the casting manufacturing process, the influence of many factors and their mutual influence leads to the appearance of casting defects, the number of which, according to various estimates, is several dozen.

The quality of castings is formed at all stages of production, starting with the design of castings and their technological development. The ability to choose the optimal alloy, to develop a technological casting determines the great possibility of obtaining a high-quality casting. Particularly responsible is the design stage of the technological process. Therefore, it is important to determine the causes of the formation of defects in castings and the quality characteristics of castings.

1. Cast irons with increased structural strength

Specificity of casting processes determines the formation of various types of casting defects (hot and cold cracks, gas-shrinkage cavities and pores, non-metallic inclusions, etc.), the formation of structural components, grain boundaries and phases, which have a significant effect on the properties of alloys in castings, workability of cast parts and products.

The presence of initial defects obtained in the cast state, and heterogeneity of the structure are characteristic of cast alloys. The origin, the location, the shape and the size of defects are determined by the composition of the alloy, manufacturability of the casting design, and the technology of its production. It is extremely important not only to find and to use effective measures for preventing formation of defects but also to be able to quantify the effect of various kinds of defects on the properties of alloys in products under their operating conditions, i.e. it is necessary to evaluate the effect of defects on the structural strength of cast alloys and to determine the operating conditions for products with defects present in them. At the same time, it should be taken into account that the structural strength of materials is largely determined by a specific type of the stress-strain state (plane-strain, plane-stress) implemented at the most dangerous stress concentrators at the crack tip.

The main requirement for alloys is to maintain a given level of properties for the entire guaranteed service life of products made of them and for the products themselves: not to break down within this period, providing the necessary level of safety and reliability.

Strength is usually understood as the ability of bodies to be intact within a sufficiently long time without being destroyed.

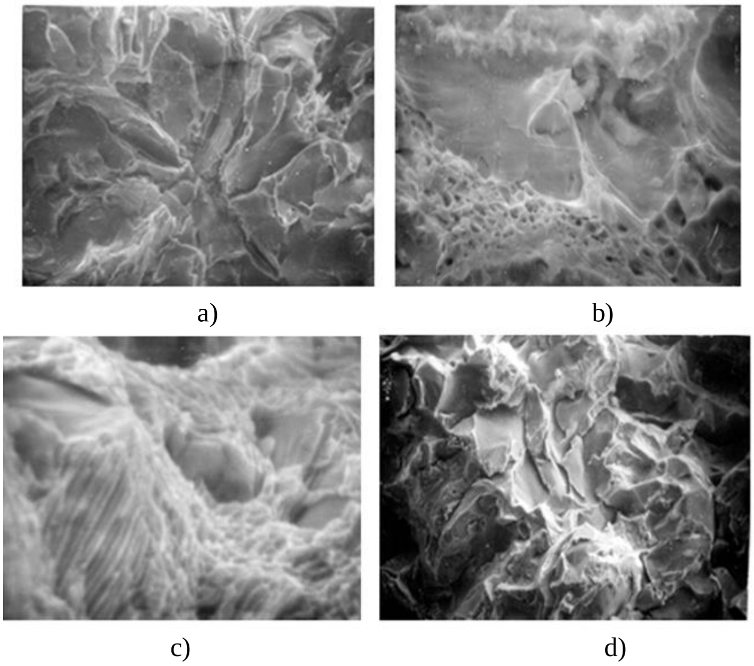
A feature of all the types of destruction is the presence of various kinds of stress concentrators that are the cause of the appearance and further propagation of cracks. Brittle fracture is especially dangerous. It is characterized by the absence of the plastic zone at the crack tip and the enormous speed of its propagation. The centers of destruction of high-strength materials are cracks of operational or technological origin, as well as crack-like defects (non-metallic inclusions, accumulation of dislocations, etc.). Cracks are sharp stress concentrators, local stresses at the top of which can be many times higher than the average design stresses.

The difference in the values of theoretical and technological strength is mainly determined by the presence in real bodies of various kinds of defects that affect the destruction processes. This led to the understanding of the inadequacy of the concept of strength as a constant of the material and the emergence of a new area that is based on a detailed study of the fracture process itself and identification of the role of cracks. This area is called fracture mechanics.

The critical stress intensity factor KIc (fracture toughness, crack resistance) was used as the main criterion for the structural strength of cast irons.

Using scanning electron microscopy on the fractures of the samples, the fractographic features of the fracture of cast irons with different structures of graphite and matrix were evaluated. Some examples are shown in Figures 1, 2.

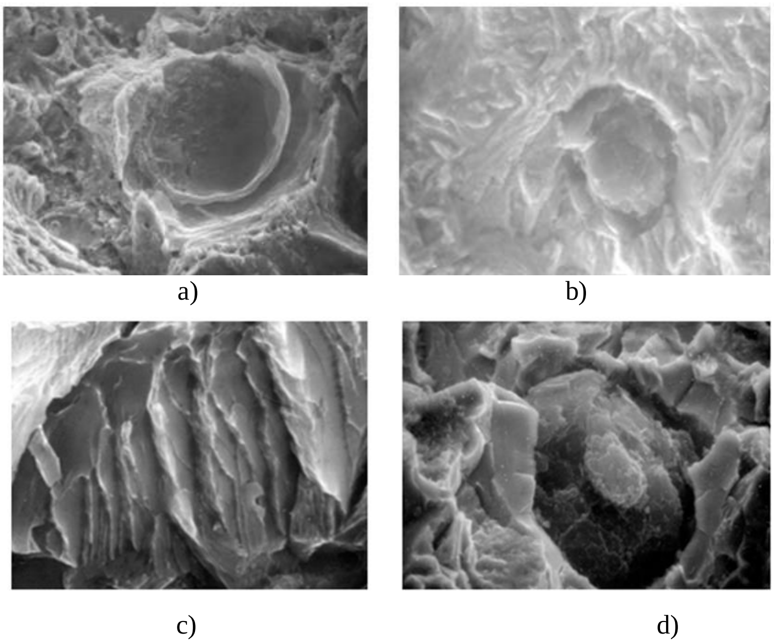
The system of regression equations obtained as a result of studying the effect of C, Si, Mn, P, S and Ni on the mechanical properties of SGI (σв, δ, KC, KIc) made it possible to determine the optimal (KIc max) composition of cast iron with spherical graphite SGI, in particular cold-resistant, and to develop the technology of its production.



a) b) c) d)

a – by graphite inclusions (SEM, x640); b – ductile fracture of ferrite (SEM, x5000); c – ductile fracture of pearlite (SEM, x5000); d – fatigue failure of pearlite (SEM, x640)

Fig. 1. – Destruction of LGI



a) b) c) d)

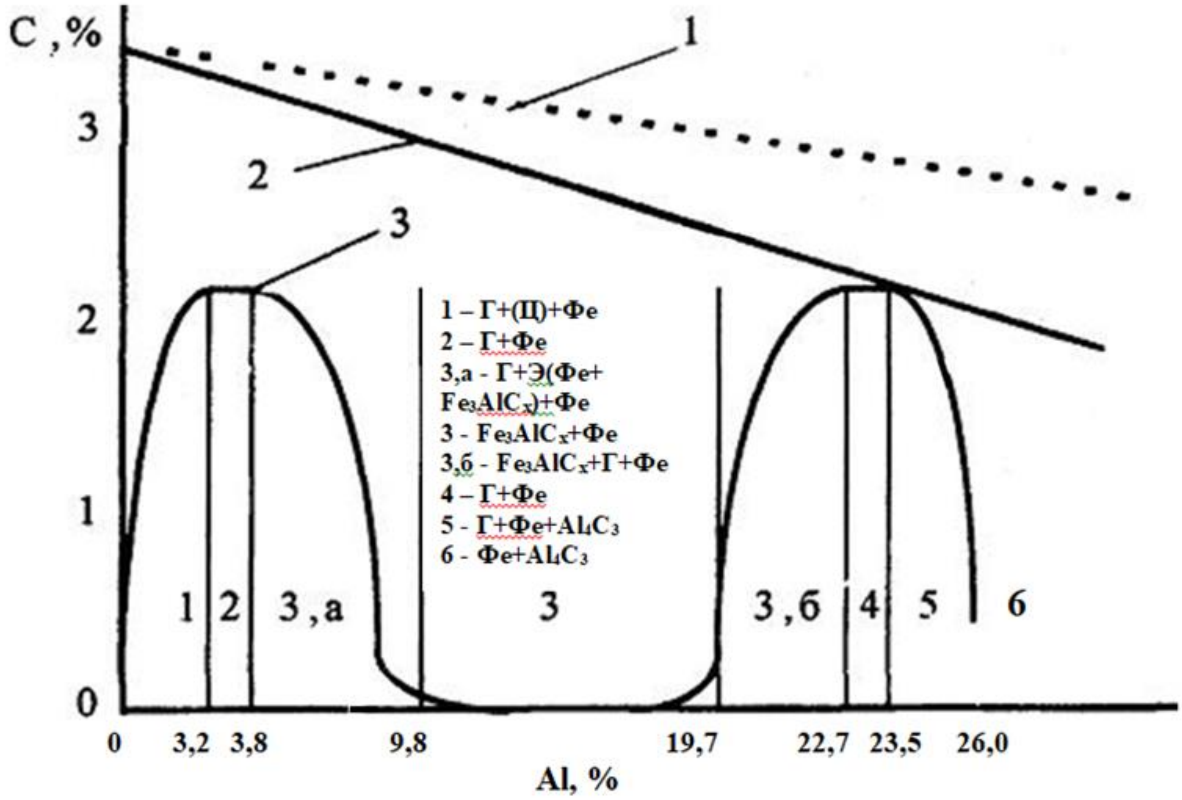
a - along the boundary of primary-secondary graphite (SEM, x640); b – ductile fracture of perlite (SEM, x320); c – brittle fracture of perlite (-1000C, SEM, x2500); d – brittle fracture of the ferrite fringe around the SHG inclusion (SEM, x640)

Fig. 2. - . Destruction of CGI

2. Aluminum cast irons

Aluminum cast irons have a number of useful properties [1, 2].

Depending on the amount of carbon released in the form of graphite during primary crystallization, synthetic aluminum cast irons (Fe-C-Al alloys) are divided into three main groups (Figure .3).



1 - theoretical carbon content, 2 - actual carbon content, 3 - graphite content; Г - graphite, Фе - ferrite, Ц - cementite, Э – eutectoid

Fig.3. - Structural zones of aluminum cast irons:

1 - graphitized low aluminum iron (LAI) - aluminum content up to 9.8% (zones 1 - 3a);
2 - non-graphitized intermediate zone iron (IAI) - aluminum content 9.8 ... 19.7% (zone 3);
3 - graphitized high aluminum iron (HAI) - aluminum content 19.7 ... 26% (zones 3, b - 6).

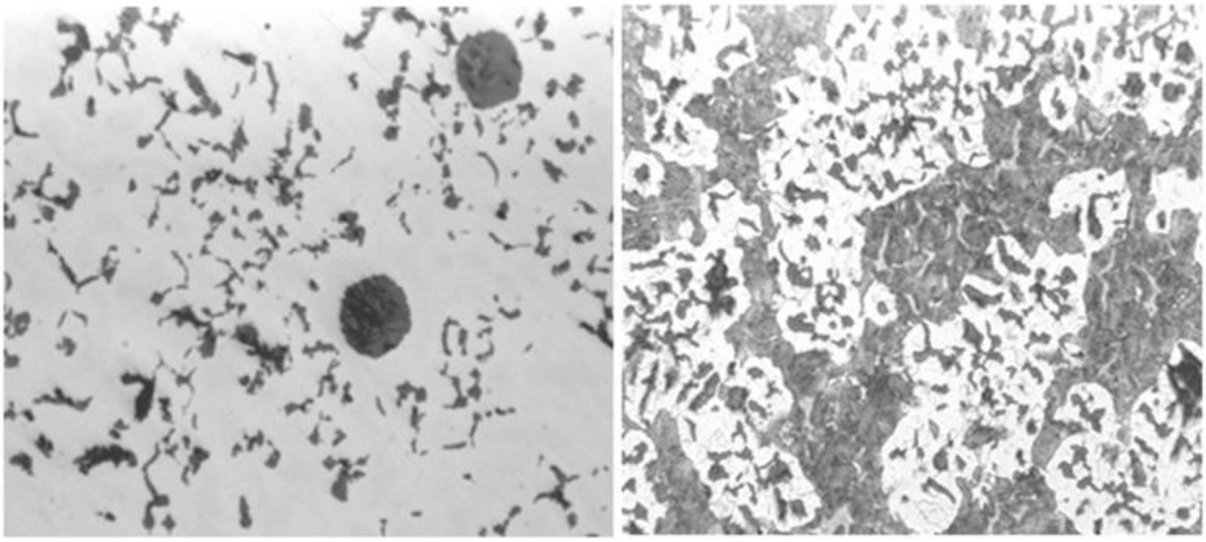
LAI, IAI, HAI possess a set of properties inherent in each of them. Therefore, it was necessary to solve specific problems to optimize their compositions and the technology of making shaped castings of them [3].

2.1 Graphitized low aluminum iron

There was studied the effect of the chemical composition (3.2…3.8%C, 0.5…2.5%Si, 2.5…5.5%Al, 0.4…1.0%Mn, 0.1…0 ,4% P), the method of introducing aluminum (into a solid charge, under the melt mirror), the overheating temperature in the induction furnace, the composition and amount of casing fluxes, the composition and amount of spheroidizing fluxes (NiMg15RZM, NiMg10 into the ladle, FSMg5 into the furnace, into the ladle, inside the mold) and graphitizing (FS75, SK30) modifiers, filtration refining on the structure and properties of LAI at different cooling rates of samples in the mold.

At the same time, in a standard wedge it was realized (spheroidal graphite/vermicular graphite): 5…1.5%, 270…360/170…220 HV. With the aluminum content of 4.0 ... 4.5%, fluidity in a spiral sample λ = 850 ... 880 mm, resistance in the sea water is higher than that of ductile iron.

Figure 4 shows the structure of low aluminum iron with vermicular graphite.



a) b)

a – not etched; b – etched with 4% HNO_3, x100

Fig. 4. - Low aluminum iron with vermicular graphite

2.2 Non-graphitized intermediate zone iron (IAI)

Until now, they have not found application as a structural material for the production of shaped castings due to increased hardness and brittleness. The studies carried out for the effect of aluminum (15...19%) and copper (up to 12%), graphitizing modification on the structure and properties of IAI made it possible to obtain partially graphitized cast iron. In cast irons of the basic composition, the aluminum content of 16% is assumed, which provides not only a half structure but also the continuity of the Al_2O_3 film formed on the surface of the samples. With introducing only copper or only FS75, the graphitizing effect does not appear. At the same time, copper increases the hardness of cast iron, accumulates at interfacial and intergranular boundaries, and when specimens with the diameter of 30 mm with the content of 3.6 and 8% copper were held at 800°C within 5 hours, the effect of "sweating" copper on the surface of the specimens was observed. Only the combined effect of copper and FS75 leads to the appearance of graphite in the IAI structure. The introduction of 0.015% cerium mischmetal provided in cast iron with compact graphite (IAICG) $\sigma_в$ =280…300MPa, σ_{cur} = 460…480MPa, 260…280NV and satisfactory machinability. At t_{per}=1480^{0}C and tpfr=1380^{0}C the developed IAICG provided λж=1050…1100 mm; while linear shrinkage was 2.3%, preshrink expansion was 0.5%, the volume of shrinkage cavities was ≈3%. Holding IAICG at 9000C within 5 hours almost doubles its electrical conductivity.

Graphitized high aluminum iron. With a reduced aluminum content, Fe3AlCx appears, with its increased content, Al4C3 appears, the presence of which leads to self-destruction of the alloy due to the interaction of carbide with water vapor according to the reaction $Al_4C_3+6H_2O = 2Al_2O_3+3CH_4$. The appearance of carbides leads to increasing the hardness, brittleness, the risk of self-destruction, deterioration in machinability, and decreasing the degree of paramagnetism of cast irons.

Under real conditions, the boundaries of the structural zones and the phase composition of these cast irons are largely determined by the charge materials, the conditions of melting and processing in the liquid state, and the cooling rate of the casting in the mold. Graphitized cast irons of zone 4 (HAI) are of the greatest interest as structural ones.

The purpose of the ongoing studies was to develop compositions and a technology of obtaining HAI with the absence of carbides in the structure at various cooling rates, which make it possible to use them for producing lightweight shaped castings.

The effect of aluminum (19...25%) and alloying elements (Cu, Ti, Zr, B, Nb), the cooling rate (V900=0.25...1.5 deg/s), the type and amount of spheroidizing modifiers in the ladle (cerium mischmetall, NiMg15RZM, NiMg10, FSMg5, SK30) and in-mold (FSMg5) modification; the composition, the method of introducing and the quantity of fluxes and slags; filtration refining (flat mesh of glass fabric coated with black carbon, volumetric ceramic and graphite in-line filters) on the structure and properties of the HAI.

The structure of high-aluminum spheroidal graphite cast iron is shown in Figure 5.

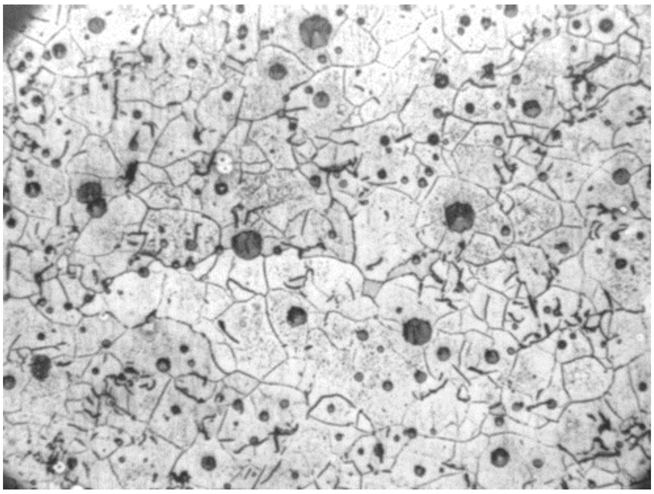


Fig.5. - HAISG structure, complex reagent, ×100

A comparative assessment of the developed cast irons resistance to hydroabrasive wear and corrosion in various media (in particular, in various grades of oil) shows that the developed high-frequency cast irons are comparable in properties to a high-nickel alloy (niresist).

The results of comparative tests of various types of cast irons for durability in aluminum melts did not make it possible to recommend the developed HAI and IAI for manufacturing crucibles and molds when melting and casting aluminum alloys.

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3. Austenitic-bainitic cast irons

Austempered ductile iron (ADI), in domestic publications also called "austenitic-bainitic" (ABISG), have been known for decades [4-7]. Castings are made of cast iron that is additionally alloyed with nickel, copper, molybdenum, taking into account the casting properties characteristic of cast iron, and then subjected to heat treatment. One of the reasons for a relatively low degree of commercialization of the production of castings made of from ABISG is the features of the second stage of the two-stage heat treatment process: austemperization in the bainite transformation temperature range of 250 – 450 ^{0}C (the first stage is austenization at the temperatures of 900 – 950 ^{0}C) associated with the difficulties of using molten salts (salt baths).

Studying the comparative evaluation of the effectiveness of using salt baths (SB) and fluidized bed plants (FBP) [8] shows that FBP can be used instead of SB during ABISG austempering. In the SB, the working medium was a melt of KNO_3 and $NaNO_3$, in the USP it was dispersed corundum, which pseudo-boiling was provided by supplying compressed air heated when passing through electric heaters. The existing differences in the conditions of cooling products in the SB and FBP can be leveled due to the composition of the cooling medium in the FBP, heating modes and gas or air supply.

The studies carried out have shown that manufacturing a casting using ABISG by vacuum-film molding, its extraction from the mold in the austenization interval, its placement in an intermediate furnace with the same temperature to equalize the temperature in the casting volume followed by transfer to the SB or FBP for austemperization, provide a significant reducing of the isothermal processing duration and the required level of mechanical properties of ABISG.

Conclusions

The developed compositions and the technology of producing cast irons and heat treatment modes were implemented in the production of large-sized castings by vacuum forming.

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Analyzing the Efficiency of Implementing PLM, PDP Systems at Machine-building Enterprises

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Abstract. PLM and PDM systems provide managing the entire information of the product and related processes throughout its entire life cycle, from design and production to retirement. The possibilities of the PDM system for designers, technologists, heads of machine-building enterprises have been presented. The approximate cost of correcting errors at various stages of the product life cycle has been indicated. The introduction of PLM systems at the enterprise KLMZ Maker LLP has been considered. The introduction of PLM and PDM systems can reduce costs by up to 2%, the pre-production time by 30%.

Keywords: technological process, labor productivity, PLM system, cost reduction, mechanical engineering

Introduction

In the present day world, it is difficult to imagine the process of developing technological and design documentation and other production processes without the use of updated information technologies. Since our country is also a part of this world, automated production management systems are also being introduced in various areas of production, and they are used at all stages of the product life cycle. This topic is very relevant and has a great potential in the development of automation of the production process in such areas as aviation and transport engineering, as well as in the defense industry.

Industrial automation with the use of information support technologies for the product life cycle is increasingly understood by business leaders interested in introducing technological innovations. Many enterprises have already carried out the automation of corporate management, accounting and financial accounting, however, the production sector often remained out of sight of managers, and in fact, it is the basis of the enterprise functioning and the most important source of profit. Production functions account for at least 70% of the costs, and it is in production activities that reserves can be found that contribute to increasing the competitiveness of the enterprise.

The use of information technologies is one of the most cost-effective ways to improve the efficiency of an enterprise, since implementing the PLM concept can reduce both production and non-production stages of the life cycle. Reducing the time of design and pre-production allows the company reducing significantly the cost of reconstruction and new construction projects, as well as optimizing the operating production costs. The most important advantage of PLM is the ability to simulate digitally not only the production infrastructure but also production processes. Correcting the project at the digital stage is incommensurably cheaper than detecting shortcomings at the project implementation stage.

The use of integrated automation systems for technological design is one of the urgent tasks of present day mechanical engineering. One of the first works on the development of continuous information support systems for the design, development and implementation of mechanical engineering products is the study by E.V. Sudov [1].

The subject of design automation received further development in the works by such scientists as A.A. Allyamovskiy, V.V. Barabanov, A.A. Kutin, S.N. Grigoryev, A.A. Sazonov and others.

S.N. Grigoryev and A.A. Kutin proved the likelihood of increasing the efficiency of innovative industries based on integrated design systems [2].

Theoretical foundations of integrated automation of design and technological preparation of production and analysis of the efficiency of implementing these systems are considered by E.V. Jamai [3, 4].

The most common tasks solved using PDM, PLM and CALS technologies are formulated by V.V. Klochkov:

- development of an integrated information system for all the divisions of the enterprise;
- automated configuration management of the subject of production;
- development at the enterprise of a product quality system that meets the international standards of the ISO 9000 series;
- development of an electronic archive of drawings and technical documentation [5].

The article by M.S. Zheleznyakova considers a strategic business approach that includes a set of commercial solutions to support the joint development, maintenance, distribution and use of product information throughout the enterprise: from the formation of an idea and concept to the end of the product life cycle.

A comprehensive solution "Product Lifecycle Management" (PLM) has been launched, which has the following key features:

- managing the entire life cycle of products: from initial planning to disposal. The optimal lifecycle management leads to increased productivity and reduced product maintenance and support costs;

- bringing together all the participants in the product development process, developing an interaction environment for maintaining and controlling the information of products and projects, managing it at all the stages of the product life cycle;
- improving the exchange of information of the product, quality and assets, developing close links between the product development process, production, quality analysis and product data management services;
- allowing companies to improve easily decision-making processes using enterprise portals, analytics and data warehouses [6].

There was studied the article by M. Cheplin that highlighted the stages of the life cycle, the problems of manufacturing enterprises.

The ways to implement the concept of PLM systems at enterprises were described. It was concluded that in order to get the maximum effect from implementing the PLM concept, it is necessary to consider all the aspects of this concept, i.e. those implemented at all the stages of the product life cycle. All the employees of the company should stop operating with the concept of "Document" (specification, drawing, etc.) and move on to the concept of "Product" as the key object of activity. The designer should not "release the documentation" but develop the product, taking into account all the features of the production and technological process, all the aspects of operation and other stages of the life cycle [7].

The article by I.G. Abramova, D.A. Abramov, R.M. Bogomolov presents a methodology for calculating the efficiency of production preparation at an engineering enterprise in the context of introducing an updated PDM system. The authors compare the key performance indicators of the PDM, SmarTeam system obtained when studying the achieved published results in the field of pre-production engineering [8].

The possibilities that the SmarTeam PDM system provides to the technologist, designer and manager have been described.

For the constructor this is the following:

- speedy mastering of the design methods established at the enterprise, due to the ability to identify quickly and view a large amount of previously developed documentation; borrowing standard solutions;
- rapid disseminating and evaluating new solutions through digital exchange of information between all the specialists of the enterprise;
- optimal using the databases of standard products, materials and other technical information;
- a favorable environment when working with CAD systems, for which SmarTeam will provide the required information, save it, track its movement, remember the current state, do not forget to create and rename a document version;
- assistance in achieving the requirements of standards, missing items (which are included) in the development of specifications, specification sheets, bills of purchased products and in the "unbundling" of products [8].

In the course of the study, it has been revealed what opportunities the SmarTeam PDM system provides to the technologist:

- a new multi-user favorable system for designing technological processes (TP), in which, when designing a TP, automatically:

a) operations, transitions, a sequence of lines describing the TP are put down;

b) forms of TP documents are formed;

c) an order card for new tooling is opened and it is additionally included in the portfolio of orders for tooling designers;

- a simple and automated mechanism of designing sketch maps in CAD systems using models and drawings of designers;
- provides the possibility of developing and using typical TS;
- provides protection against errors when writing product designations, basic materials and technological information that was previously entered into the database by designers, fellow technologists and other specialists in the course of their work;
- provides a mechanism for working with "cases" and consumption rates of materials with calculations of specified and summary consumption rates [8].

The features of the SmarTeam PDM system for the manager are as follows:

- to give tasks in digital form and see the results of all the kinds of subordinates without getting up from the workplace;
- to comprehend calmly the technical aspects of the project, compare with previous developments, to make notes on electronic documents that are submitted by subordinates for verification and approval;
- to analyze the timing of the project implementation using statistics and the possibility of organizing dispatch requests [8].

The noted capabilities of the system at the qualitative level allow expecting the following results for the technologist, designer and manager:

1) reducing the production preparation time;
2) increasing the quality of projects;
3) increasing the qualification education and, thus, demand;
4) peace of mind in the face of ever-increasing demands for reducing the design time and improving the quality of projects.

The noted point: "reducing the preparation time" must be confirmed and quantified.

The topic of introducing PLM technologies is very relevant, since the efficiency of any machine-building enterprise depends on such factors: the dynamics of using the renewal of service stations, the widespread introduction of equipment with numerical control (CNC), machine tools such as a “machining center” (MC), industrial robots and manipulators (IRM), robotic complexes (RTC), flexible production systems (FPS), flexible production modules (FPM), including in the development automated systems that help to reduce the time of design and pre-production, to reduce the cost of reconstruction and new construction projects, as well as to optimize operating production costs.

1. Research methods

Possible errors can be found and corrected already at an early stage of design. According to the estimates of the analytical company Gartner Group, the cost of fixing an error at various stages of the life cycle is the cost presented in Table 1.

Table 1 - The cost of fixing an error at various stages

Pre-production stage	The cost of fixing an error
Conceptual design	$1
Product design study	$10
Making a product layout	$100
Tooling design	$1 000
Tool making	$10 000
Release of the installation series	$100 000
Mass production	$1 000 000

To assess the economic efficiency of PLM implementation, such indicators as return on investment (ROI), total cost of ownership (TCO), cost benefit (Cost Benefits Analysis, CBA) are used.

Let's evaluate the effect of investing in PLM using the ROI indicator, which is characterized by the ratio of the cost of investments and the benefits that they bring

$$ROI = \frac{(a-b)}{b}, \quad (1)$$

where a is the benefit from implementation,
b is the investment costs.

The ROI indicator largely depends on the industry and production specifics of the enterprise. However, there are general enterprise-independent benefits that PLM brings.

General increasing the labor productivity. It is achieved through increased individual productivity of employees, globalization and distribution of business, and increased collective productivity. At the same time, the individual productivity of employees is increased by optimizing the working time consumption: employees spend more time for their direct duties and less time for supporting functions. There is an opportunity to cooperate effectively with geographically distant partners and to distribute their production capacities. The productivity of teamwork increases: the number of erroneous decisions made by counterparties due to their outdated initial information is significantly reduced.

General reducing the material costs. It is achieved by taking into account the requirements for the object in detail at the early stages and tracking their feasibility in the future, which makes it possible to identify most of the erroneous decisions in the virtual prototype of the object, and not in its physical embodiment. This significantly increases the number of borrowed and standard solutions.

Increasing overall profit. It is achieved by reducing the time of project implementation in comparison with competitors.

As a result, if the benefits listed above are converted into quantitative parameters, you can get the following formula for calculating the ROI from the implementation of PLM:

$$PLM\ ROI = \frac{(c-d)}{d}, \quad (2)$$

where c is the benefit (from increasing productivity, profit increasing, cost reducing),
d is the investment costs in the PLM.

According to the analytical company Gantry Group, the PLM implementation efficiency is presented in Table 2.

Table 2 – The PLM implementation efficiency

Advantages	Efficiency
Increasing labor productivity	43%
Reducing the design time	46%
Improving the efficiency of interaction with counterparties	74%
Capitalization of knowledge, reuse of developments	44%
Compliance with the production schedule	20%
Reducing production costs	25%
Improving the product quality	32%

In monetary terms, the return on investment from the PLM implementation should be considered as a phased process, stretched over the life cycle of an object.

Figure 1 shows life cycle cost curves with the use and without PLM. The area between these curves characterizes the quantitative measure of the benefits from the PLM implementation.

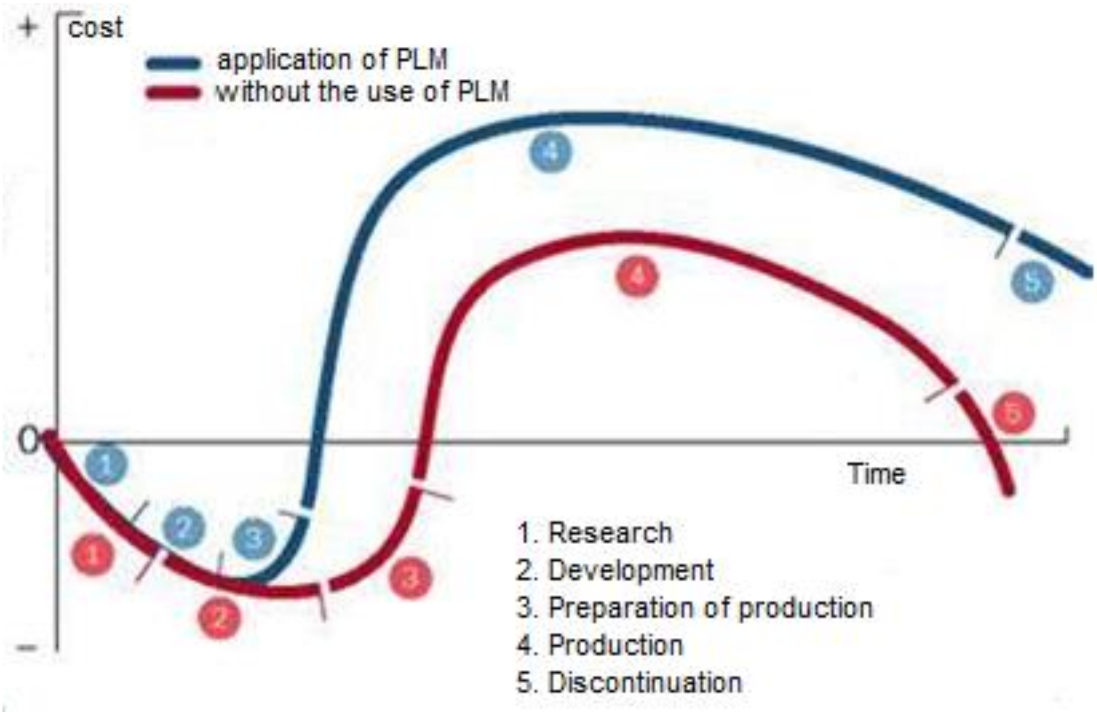

Fig. 1. – The curves of the life cycle cost

At the research stage, the introduction of PLM increases the efficiency of interaction between the team members, and the presence of a single information space allows completing the research process much faster and starting the development process. Due to the centralized storage of all the data, it becomes possible to quickly include new participants in the research process.

The introduction of PLM allows reducing the duration of the development stage by increasing the efficiency of interaction, increasing the number of reusable parts and borrowed solutions, reducing the cost of eliminating erroneous decisions originally incorporated into the product or object.

The duration of the pre-production stage is also significantly reduced with the PLM introduction due to the fact that by the beginning of this stage we have a complete and reliable specification for the manufactured product. Specialists responsible for the preparation of production have the opportunity to simulate production processes on a virtual prototype of the product and to prevent possible problems in advance.

Thus, supporting the manufactured products at each stage of the product life cycle is now becoming an absolute requirement for a present day industrial enterprise. PLM technologies are increasingly being used in the domestic industry: enterprises are moving towards the development of a single information space, both at individual enterprises and within holding structures, which is in line with global practice.

2. Results and discussion

2.1 Implementing PLM systems at the KLMZ Maker LLP

For automation of the enterprise, software solutions from different developers were considered and compared. Designers, technologists, CNC programmers tested and selected the NX+Teamcenter because these products:

- can close all the existing and planned tasks of design and technological preparation;
- have a wider functionality, intuitive interface;
- allow providing the end-to-end process of CTPP based on one 3D model, from conceptual design to machining and assembly in the shop.

The Maker LLP planned to purchase expensive CNC machines. The NX CAM is the recognized leader in CNC programming systems. Therefore, in terms of CAM, the choice was obvious.

The weighty factors in selecting the systems were also their compliance:

- with international standards;
- with present day concepts in mechanical engineering.

This is important for businesses that are looking to the future, planning to scale and to change in a bustling digital world. Rapid introduction and development of new technologies allows increasing the competitive advantage and maintaining the leadership.

The PLM project was part of the Maker LLP modernization plan. The Teamcenter platform from the Siemens Digital Industries Software was selected as the PLM system.

Before the deployment of the PLM project, a pilot project was implemented at the LLP site using the Siemens PLM Software solutions. Its goal was not only to develop a digital model of the excavator assembly but also to evaluate the operation of the Teamcenter system in real plant conditions and the employees’ perception.

The first part of the pilot project, automation of design preparation for production (DPP) was successfully completed within the designated short time of 6 months. The designers have experienced the convenience of working in conjunction with the NX systems and the Teamcenter. After that, the decision was made to deploy the Teamcenter at the enterprise design office. The second stage of the pilot project, technological preparation of production (TPP) was completed in a year, which is a very good result.

As a result of the pilot project, it was decided to execute new projects of excavators only under the control of the Teamcenter

2.2 Organizational aspects of implementing the PLM system

The success of introducing automated systems at the enterprise largely depends on the position of its first person, the head. There is needed an administrative resource, the will of the first person and his organizational actions [2]. CEO of the Maker LLP acted as the curator of the PLM project and its active participant. To ensure the success of the launched PLM project, the Maker LLP formed a small team consisting of the most competent and advanced designers and technologists interested and passionate about the PLM project. It was assumed that this team would continue to support the system and to develop it.

When starting a new automation project, the management of an enterprise is very often faced with an important problem: to break resistance of the heads of structural divisions, who begin sabotaging this process. Objectively, they really get into a difficult situation. They get a whole new job. They are psychologically unprepared for this, they are afraid to fall out of the process and do not want to take on additional risks. It is very difficult to introduce innovations into such a linear structure of personnel.

Something similar happened at the Maker LLP. At the time of introducing the electronic layout technology, all the chief project engineers (CPEs) of the enterprise, being good subject specialists, were aged people, and it was quite difficult for them to change radically the design tool. In turn, the work departments that received the paper layout from the CEPs did not see the point in digital design.

To facilitate the initial stages of implementation, it makes sense to carry out structural changes: temporary, and if needed permanent. The management of the enterprise offered the CEPs to educate their successors, specialists who, having adopted their subject competence, could play the role of CEPs in the context of the introduction of digital technologies. The competition was organized to train young personnel. As a result, specialists capable of performing the functions of CEPs were trained in a relatively short period of time.

Automation of design preparation of production

All the participants in the design process must work in a certain virtual space and design the product as a single electronic layout in the global coordinate system, neither in pieces nor in compartments but as a single product. Everyone sees each other's work. Each element is developed in relation to the existing context, including associative binding. Any complex design begins with a conceptual image, search for diagrams, layouts, structural power diagrams, strokes, and development of detailed design documentation. The output is design documentation in the form of an electronic layout.

At the Maker LLP, the work at developing products is carried out using the technology of electronic layout. This is one of the important achievements of implementing the PLM system at the enterprise.

Using the PTS (Product Template Studio) functionality in the NX system in the DB, the Maker LLP was able to implement a digital layout template. By setting the global parameters of the product in the template specified in the electronic terms of reference, a digital layout diagram of the excavator is formed.

The essence of the PTS approach is that the parameters that determine the design of a part or subassembly are linked in advance by mathematical dependences. The PTS template accumulates all the knowledge about a certain class of products, and the layout diagram of a specific product corresponding to the TS is obtained automatically. To speed up the design process, it is needed to develop a set of PTS templates for the most frequently repeated features or assemblies. In the future, the designer will be able to refine them with minimal time costs.

The Maker LLP uses NX techniques for large assemblies. The total assembly of an excavator can include up to 10,000 components. It was decided to refuse downloading the entire assembly at the workplace. Instead, only its context is loaded, the environment of those details on which the topology of a particular designed node or assembly depends. To automate this process, contexts are used that are created by combining various filters (by mass, volume, size, distance from a point; all details that fit into a geometric primitive, etc.).

At the stage of developing the project of the largest excavator EKG-50, the designers of the enterprise mastered the PMI technology (means for supporting production information). PMI is applied to 3D models in order to finally get away from the need to print drawings. The NX 9 release offers rich possibilities for using PMI in pre-production and CNC machining programming with the NX CAM module.

The company has approved a normative document (standard) proclaiming as an original a 3D model of a product equipped with PMI information. This condition applies to all the new products.

Integration of the Teamcenter and the Cortona3D Rapid Author allowed developing interactive catalogs and guidelines, and the technology department developed animated assembly flow sheets.

Regulatory support is one of the very important aspects of the implementation of PLM technologies. Before accepting the concept of developing the information space of the Maker LLP at the enterprise, all the processes were described in the IDEF0 notation. A number of directories were created in the Teamcenter, the data transfer from PDM to the enterprise ERP system was established. There is a group of reference information (RI) that ensures the unity of directories for all the systems of the enterprise (at any given time, all the directories are available, relevant and identical).

2.3 Production technological preparation

At the Maker LLP, the presence of an electronic layout of the product with all the attribute information (PMI) necessary for the production preparation was an important prerequisite for implementing the digital process of technological production preparation.

All the new excavator projects at the Maker LLP are done in the Teamcenter environment. For example, the EKG-12 M project is already being carried out using a new technology with the use of electronic terms of reference and parametric templates.

It is very important for technologists to work in a single information space with designers. This allows using simultaneously (without waiting for the complete development of a new product) the design results for the TPP. For process participants, an effective unified system of presenting and distributing information of all the aspects of the product is being developed. For example, the overall dimensions of a part and its material are determined much earlier than its detailed study is completed. The information of the dimensions and material can be transferred to the technologist and supplier without waiting for the release of a fully developed model. This allows the technologist starting the wort at the TPP much earlier. The suppliers, on the one hand, may not to perform useless detailing work if the semi-finished product for the part cannot be purchased or processed, and on the other hand, it provides the necessary reserve for preparing the optimal supply contract.

At the Maker LLP the TPP in 3D design involves the use of:

- 3D models for developing control programs for CNC machines;
- 3D models for developing technological blanks with the definition of allowances;
- electronic layout for designing associative technological equipment;

- structures of models of an electronic layout for testing assembly technological processes and technical processing processes, creating all necessary technological sketches (including animated ones, video).

The workflows developed in the Teamcenter are considered electronic originals of technological documentation.

In the course of implementing the pilot project, specialists were able to simplify significantly the process of TPP and technological documentation, and made the necessary changes for technologists in the Teamcenter Manufacturing 8.3 interface to make it more convenient for work.

The process of TPP on the electronic layout of the product takes place in the Teamcenter system and differs significantly from the traditional one. The USTD documentation is treated in this process as a report generated automatically based on various information stored in the Teamcenter objects. In the future, the Maker LLP will refuse such paper reports altogether, when the workshops will be equipped with tablets and monitors, and the workers will be connected directly to the Teamcenter.

The assembly process in the Teamcenter is presented as a visual 3D animation; technological sketches that define the process of machining parts on universal equipment are presented as a set of 3D models, each of which describes a specific operation.

The digital process of the TPP takes place in a single virtual space, which allows working out all the changes in the design through an associative chain. The Maker LLP implements the following TPP tasks:

- maintenance of interdepartmental routes in the Teamcenter Manufacturing environment;
- automated material rationing in the Teamcenter Manufacturing environment;
- design of the assembly TP and machining on universal equipment in the Teamcenter Manufacturing environment;
- formation of technological reporting documentation;
- visualization of assembly TP using the Cortona3D in the Teamcenter environment.

The task of maintaining an inter-shop route was solved by developing a special software shell that, using the built-in functions of the Teamcenter Manufacturing, forms a cover structure according to certain rules. The shell has a simple and intuitive interface that displays the information from the Teamcenter classifier, eliminates the errors that are inevitable with manual entry, and reduces the complexity of creating a route for product components. The interface allows managing simultaneously several cases for one PAU and make changes.

For the tasks of the material and labor rationing, employees developed a module in the Teamcenter environment, which is based on a powerful mathematical apparatus. This solution allows calculating almost automatically, using the data of the classifier for materials, the norms for various scenarios. The developed module allows normalizing several grades of materials at once, depending on the parameters of the workpiece and the conditions of purchase. In the module for the formation of technological processes, the mechanism of labor rationing was implemented both for operations and for transitions.

Due to the outstanding dimensions of the Maker LLP excavators, they are not fully assembled on site. But individual nodes, the complexity of which is quite large, are still assembled in workshops. Visualization of technological documentation made it possible to take this process to a completely different level due to a significantly better study of the product for assembly and the possibility of automated changes, which was facilitated by the tight integration of the Teamcenter and the Cortona3D. At the same time, animated assembly processes can be viewed both in the Teamcenter environment and on any other computer or mobile device of employees without the Teamcenter installed.

Table 3 – Calculating the economic efficiency

Costs of personnel	Amount
The number of designers and technologists	800 prs.
The total cost of maintaining one person per year (salary, indirect costs, etc.)	720 th.tg.
TOTAL per year:	576 mln. tg.
One-time costs for software and hardware	
Average cost of PLM software for an engineering worker	300 th.tg.
The cost of additional modules	500 th.tg.
Hardware cost	1 mln. th.
TOTAL:	1 800 th.tg.

Permanent costs	
Cost of maintenance and updates (assumed at 25% per year)	6.3 mln. tg.
Tuition fee per year	500 th.tg.
Implementation cost (first 2 years)	10 mln. tg.
Support cost (after 2 years of the project)	4 mln. tg.
TOTAL per year (first 2 years of the project):	16.8 mln. tg.
TOTAL per year (after 2 years):	10.8 mln. tg.
Features of projects and production	
Number of new projects per year	2
Number of models/drawings per project	2000
Number of design and technological changes per year	5000
Prototyping	
Number of new projects per year	2
Average number of prototypes per project	2
Average cost of a prototype	0 mln. tg.
TOTAL per year:	40 mln. tg.
Using the working force	
Designing to create new products	10%
Making engineering changes	40%
Finding documentation	10%
Developing and transferring compositions of products	5%
Preparing and holding meetings	3%
Developing models (3D)	2%
Developing demonstration and methodological materials	5%
Correcting errors in drawings	10%
Correcting/translating imported drawings, models, etc.	15%
TOTAL:	100%

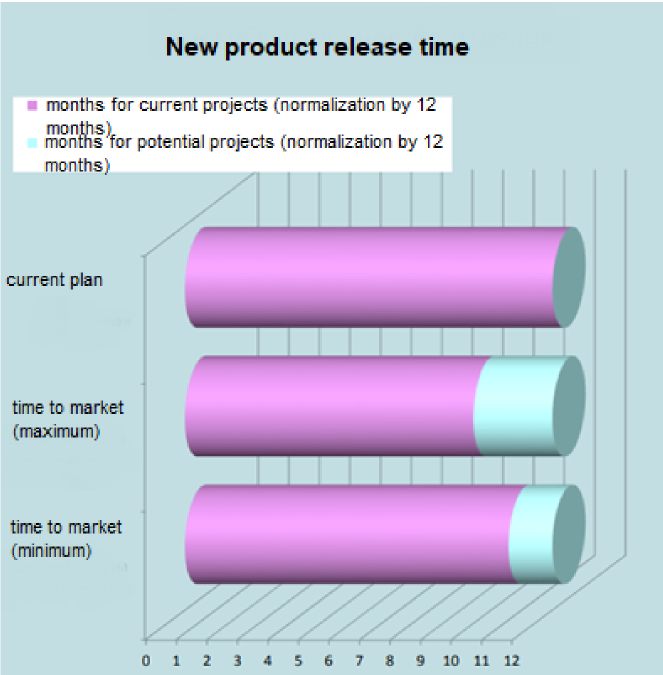

Fig. 2 – The time of the new product release

Conclusions

The PLM technology implemented at the Maker LLP based on the Siemens PLM Software products allows obtaining complete information of the product at all the stages of its life cycle.

The enterprise has already experienced a number of specific benefits of PLM. Firstly, at the stage of assembling the excavator, the number of collisions has significantly decreased. Previously, in a quarry abnormal situations often arose during assembly, which were always very difficult to correct in the field. Secondly, the number of notifications of changes has decreased by an order of magnitude. Thirdly, the product design process has been reduced in time.

Before the introduction of PLM, it happened that at the stage of the detailed design significant deviations of the design from what was indicated in the TS for the excavator were found out. Eliminating such errors generated by the wrong design approach, was very difficult and time consuming. Today, the approach adopted at the enterprise provides for the mandatory development of an electronic layout and design in the context of assembly, which completely eliminates such situations. One of the important effects of using the Teamcenter for designers is to streamline the work with models and large assemblies that no longer fall apart.

Designing in the NX environment accelerated the work of designers by one and a half times (on a specific excavator project). Since specificity of the enterprise lies in the fact that the finished product is assembled directly in the customer's quarry, the ability to assemble the product immediately without problems and to rework is extremely important. In this aspect, the Siemens PLM technologies give the enterprise a huge impact.

The Maker LLP technologists have found it easier and more convenient to work with 3D models designed in NX using the electronic layout technology. Previously, they often had to redo them, since the requirements and rules of construction were violated in the initial process.

The maximum task of the Maker LLP is to develop an electronic excavator that can be sold to the customer by demonstrating it only in the form of an electronic layout (figure). Accordingly, on the basis of an electronic layout, the operational documentation is developed in accordance with international standards.

The conducted studies have shown the following:

1. The use of the PDM system reduces the production preparation time. For example, the cycle of design and technological preparation for the production of bits and drilling equipment is reduced by 30%;

2. The payback period for the PDM system is about 3 years;

3. The use of the PDM system helps to reduce the total gross costs of machine-building production in the amount of 1 ... 2%;

4. The use of the PDM system helps to achieve the worthy goal of the enterprise: providing competitive advantages in the strategic area of its management.

Summarizing domestic and foreign experience in the field of automation of design and technological preparation of production, it was concluded that in order to solve effectively the problems of developing innovative products in mechanical engineering, a comprehensive justification for the introducing there are needed methods and means of automating the design and technological documentation at domestic enterprises.

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A Prototype of a Multi-speed Gear Hub for Manual Wheelchairs - a Preliminary Analysis of the Dynamics of the Wheelchair's Motion and the Biomechanics of the Human Body

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Annotation. The aim of the article was to analyze the motion dynamics of the human-wheelchair anthropotechnical system and the biomechanics of the human body for the purposes of designing innovative manual drives. The conducted analyzes derived simplified equations of the moment of resistance to motion and reaction forces loading the wheelchair frame. These data are the input parameters in the process of designing the drive system of the wheelchair. The result of the described works is the development of two technical solutions using the data obtained on the basis of the presented dynamic and biomechanical analysis.

Key words: wheelchair, propulsion, mobility, propulsion biomechanics, multi-speed drive, planetary gear, wheelchair manual drive, manual propulsion

Introduction

Nowadays, we observe a significant increase in the population of physically disabled people who have to use wheelchairs for everyday functioning. About 75% of wheelchair users can use manual drives to ensure mobility. Bearing in mind the comfort and health care of users of manual wheelchairs, the Rehabilitation Engineering Research Center on Technology Transfer organization [16] was established at the University of Buffalo, NY, associating engineers, physiotherapists and entrepreneurs involved in the sale of rehabilitation devices. During its work, this group expressed the need to design and implement multi-gear gears for traction drives. They noticed that the user has to put a lot of effort to propel the wheelchair. As a result, it is susceptible to numerous injuries, such as corns on the hands, muscle tears and joint dislocations. According to the diagnosis carried out by T2RERC, about 51% of wheelchair users suffered an injury to the upper limbs as a result of its propulsion. It should be remembered that an injury to the upper limb of a manual wheelchair user in a significant number of cases means the inability to function independently in everyday life.

In addition to the injuries that a manual wheelchair drive can cause, attention should be paid to environmental and human factors that reduce the mobility of manual wheelchairs. Field conditions, such as surface hardness and slope, have a great influence on the user's effort, these problems appear especially in developing countries and old urban agglomerations.

1. Wheelchair motion resistance and their impact on the anthropotechnical system

Today, about 66% of grinding bodies worldwide are produced from steel by cross-helical rolling on ball rolling mills, 13% are steel cylinders ø20-30 mm (cylpebs), and 16% are cast iron balls and cylpebs, 5% - others [4, 5]. The characteristic value describing the dynamics of the wheelchair is the torque of the drive wheel Mnap, called the drive torque. It is responsible for propelling the trolley, and thus overcoming the force of rolling resistance Fop and generating the driving force responsible for accelerating the trolley. The drive torque (1) can be divided into the braking torque M_h (2) and the moment of inertia M_b (3) coming from the acceleration of the trolley. The braking moment comes from overcoming the forces of resistance to moving the cart resulting from the rolling resistance force F_{ot}, the uplift resistance force and the aerodynamic drag force F_{ar}.

$$M_{nap} = M_h \pm M_b \tag{1}$$

$$M_h = \frac{1}{2} F_{op} d = \frac{1}{2} (F_{ot} + F_{ow} + F_{ar}) d \tag{2}$$

$$M_b = \frac{1}{2} m a_w d \tag{3}$$

When driving the trolley, the drive torque M_{nap} is equal to the sum of the braking torque M_h and the moment of inertia M_b. On the other hand, during the return phase of the hand or during braking, the drive torque is equal to the difference between the braking torque and the inertia. The value of the drive torque is influenced by many factors, such as: mass of the system mu, offset of the hip joint from the axis of rotation of the rear wheels l_b, angular acceleration of the strings ε_c, coefficients of load distribution on the front and rear wheels, coefficients of rolling friction of the front wheels k_1 and rear k_2 and the slope of the terrain β. Factors influencing the drive torque can be listed much more, but they are so difficult to visualize or insignificant that they are usually omitted.

It should be noted that when driving on level ground, the braking torque is small, while the moment of inertia (Fig. 1) reaches high values $M_b >> M_h$. This situation changes when driving up a hill, then the braking torque increases proportionally to the angle of inclination of the hill being overcome. The course of the torque change is shown in the graph below (fig. 2). This graph shows the change in the braking torque for a constant displacement of the hip joint from the axis of the rear wheels l_b backwards by 50mm, the weight of the system mu of 90 kg, and the variable value of the friction coefficient f_1, f_2 and the variable slope of the terrain β.

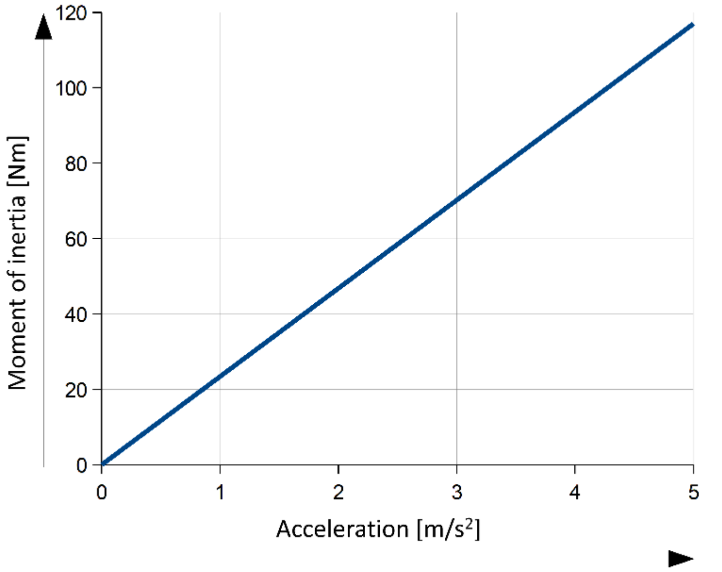

Fig. 1. – Changing the value of the moment of inertia of the trolley depending on its acceleration

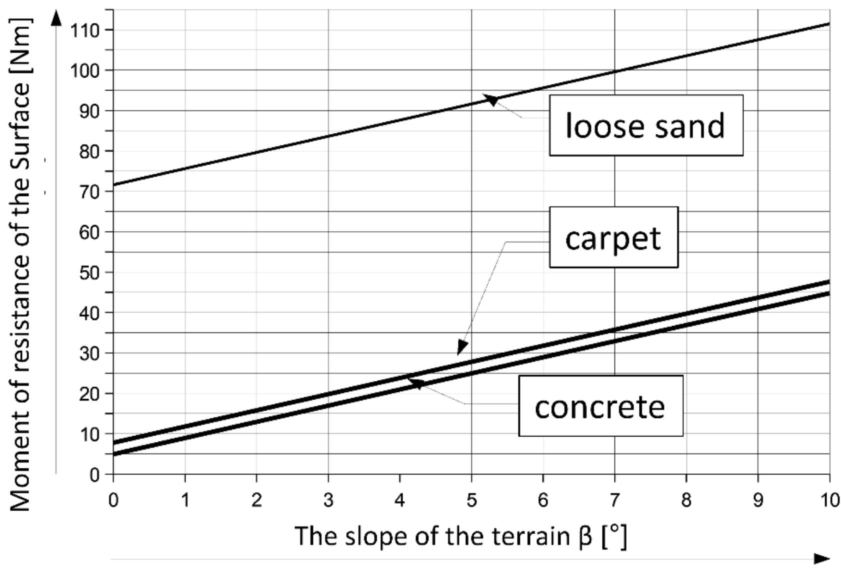

Fig. 2. – The value of the braking torque for three different surfaces depending on the slope angle

In order to verify the thesis put forward by the Rehabilitation Engineering Research Center on Technology Transfer, it was decided to examine the impact of the drive torque on the human muscular system. Only one upper limb was included in this study, so the composite drive torque value should be multiplied by two to obtain the correct drive torque value generated by the two upper limbs. The magnitude of the drive torque affects the user's effort directly proportionally. This effort can be measured as a percentage using the AnyBody Modeling System software [14]. In this software, the user's effort is described by the MMA parameter - maximum muscle activity. Its value is expressed by the maximum product of muscle strength F_m and muscle strength F_0 in a given position of the limb (4).

$$MMA = \frac{F_m}{F0} \times 100\% \tag{4}$$

Example values of maximum MMA muscle activity are shown in the graph (fig. 3). Three lines reflecting the change of the MMA parameter for three values of the driving torque Mnap: 20 Nm, 15 Nm, 10 Nm have been plotted on this graph. In this study, only the value of the driving torque was variable, which did not take into account the change in the active part of the muscle force FEF [9]. The constant elements in the study were the angular acceleration of the strings, the position of the body in the wheelchair and the angle of rotation of the strings.

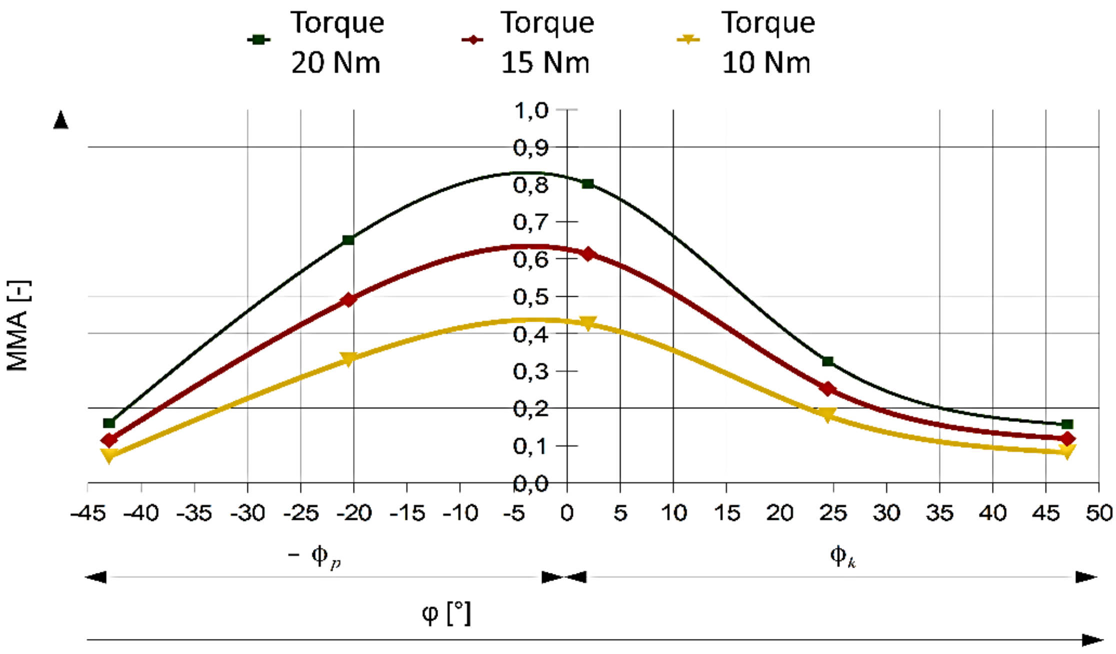

Fig. 3. – Graph of the muscular effort of one upper limb expressed by the maximum muscular activity for three values of the half of the drive torque of the strings

Based on the analyzes carried out, it can be seen that there is a need to use hand drives with the function of multiplication i > 1 and reduction i < 1 of the drive torque supplied to the strings. Such a drive should operate in the reducer mode when driving up hills or when driving on difficult terrain. In the case of driving on an even terrain, the multiplier function would increase the speed of the trolley without the need to increase the frequency of driving movements. In addition to the above-mentioned functions, such a drive should have a neutral gear with a 1:1 ratio, which would be used when driving in closed rooms or when driving the stroller peacefully.

2. Wheelchair dynamics

Wheelchair movement is an anthropotechnical system that is difficult to describe mathematically [2]. These difficulties result from the unpredictability and unique physical abilities of a wheelchair user. Observing the movement of the wheelchair, it can be stated that it moves with a non-uniformly variable movement [7,8]. In order to save the mathematical model of wheelchair motion, a simplification can be made, which assumes that the wheelchair moves with uniformly variable motion (Fig. 4). This simplification reflects the actual movement of the wheelchair with sufficient accuracy while simplifying the calculations.

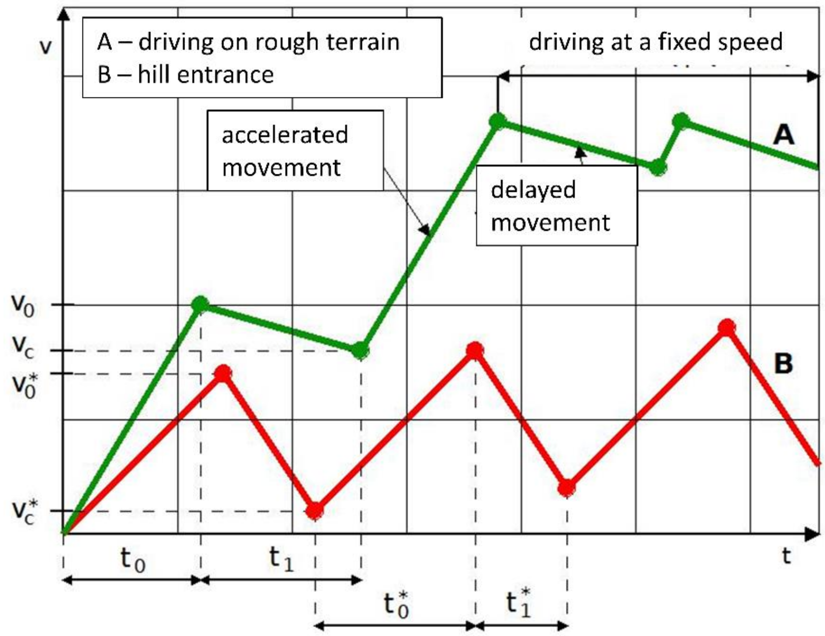

Fig. 4. – Diagram of the speed of the truck depending on the duration of movement, for two road situations: A - driving on level ground and B - driving up a hill

The entire movement of the trolley consists of two elementary movements: uniformly accelerated when driving the strings and uniformly delayed when the hand returns to the initial position on the strings (Fig. 4). Due to the assumed uniform nature of the wheelchair motion, the constant angular acceleration of the strings ε_c caused by the transmission of muscle forces by the upper limb was assumed in further considerations. The propulsion motion was divided into two phases: the propulsion t0 and the return t1 [1, 3, 11]. For driving on level ground, uniformly accelerated motion is included in the time interval $0<t<t_0$, while in the case of driving uphill it belongs to the interval $0<t<t_0^*$. Uniformly retarded motion while driving on level ground is included in the time interval $0<t<t_1$, and for the uphill climb this interval is $0<t<t_0^*$. The difference in the lengths of the adopted compartments results from the nature of the driving motion, which depends on the terrain conditions. When driving on level ground, the duration of the drive phase t will be shorter than when driving uphill. The prolongation of the drive phase time during the uphill climb t_0^* is due to the fact that the user must generate greater muscle strength, which results in the extension of the force generation time [10]. The inverse relationship can be observed in uniformly decelerated motion. In this case, when driving on level ground, the time of the return phase of the hand t1 is longer than the time of the return phase of the hand when driving up a hill t_1^*. This dependence results from the fact that when driving up a hill, the braking acceleration ah resulting from the rolling resistance of the wheelchair [12] is so high that for longer times of returning the hand to the initial position, it would result in the wheelchair moving back.

Based on the presented graph (Fig. 4), the assumed time intervals and the known constant angular acceleration of the strings, the acceleration of the wheelchair (5) and its velocity v_0 (6) can be determined for the time intervals $<o;t_0>$ and $<0;t_0^*>$. These intervals define the duration of the drive phase in the entire drive motion.

$$a_w = \varepsilon_c \frac{1}{2} d \tag{5}$$

$$v(t) = a_w t \rightarrow v(t = t_0) = v_0 = \frac{1}{2} \varepsilon_c d t_0 \tag{6}$$

As can be seen from the above relationships, the acceleration of the wheelchair aw depends to a large extent on the diameter of the drive wheel d. torque flow from the strings to the wheel. Assuming that the user uses such a device, we can introduce the parameter i defining the ratio between the strings and the wheel (7) into the above formulas.

$$v_0 = \frac{1}{2} \varepsilon_c i d t_0 \tag{7}$$

In the propulsion movement of the wheelchair, immediately after the propulsion phase, there is a return phase caused by the return movement of the hand to the initial position. This phase, depending on the road situation, can be described by the following intervals: $<0;t_1>$, $<0;t_1^*>$. During the return phase, the wheelchair is not affected by the force of the upper limb, but by the rolling resistance force F_{op}, which generates the resistance acceleration called braking acceleration ah (9). The rolling resistance force (8) depends on several elementary component forces: rolling resistance force F_{ot}, elevation resistance force F_{ow} and aerodynamic drag force F_{ar} [4]. These components, in turn, depend on the weight of the wheelchair with the user m, the speed of the wheelchair, the rolling friction coefficient of the wheels and the efficiency of the rolling elements in the wheelchair structure.

$$F_{op} = F_{ot} + F_{ow} + F_{ar} \tag{8}$$

$$a_h = \frac{F_{op}}{m} = \frac{F_{ot} + F_{ow} + F_{ar}}{m} \tag{9}$$

As a result of the braking acceleration and the user not propelling the strings, the wheelchair starts to slow down. The kinetic energy equation can be used to calculate the velocity of the cart at the end of the entire driving motion v_c. It can be assumed that the kinetic energy E_k at the end of the drive motion, i.e. for $t=t_0+t_1$, will be equal to the sum of the kinetic energy obtained in the uniformly accelerated motion and the uniformly retarded motion (10).

$$E_k(t) = E_{kt_0} + E_{kt_1} = \frac{mv_0^2}{2} - \frac{mv(t)^2}{2} = \frac{mv_0^2}{2} - \frac{m(a_h t)^2}{2} \tag{10}$$

It should be noted that the kinetic energy in the drive phase E_{kt0} depends on the speed obtained from the acceleration of the strings ε_c driven by the user. On the other hand, the kinetic energy of the return phase E_{kt1} depends on the speed resulting from the braking acceleration a_h, which gives this energy a negative value. After simplifying the equation of kinetic energy, we obtain the equation of velocity depending on the duration of the return phase $0<t<t_1$ (11) and the equation of the velocity of the cart at the end of the driving motion v_c (12).

$$(t) = v_0 - a_h t \tag{11}$$

$$v_c = \frac{1}{2}\varepsilon_c i d t_0 - \frac{F_{ot} + F_{ow} + F_{ar}}{m} t_1 \tag{12}$$

3. Biomechanics of propulsion of a manual wheelchair

An important aspect when describing the dynamics of the trolley is to determine the type of manual drive used. Currently, the most popular are traction and lever drives [12]. The most important feature of the manual drive affecting the dynamics of the wheelchair is the angle of rotation of the driven element (Fig. 5)[6]. This angle can be divided into the initial angle $-\phi_p$ representing the maximum position of the hand in the initial position, and the angle ϕ_k describing the maximum position of the hand in the final position. The maximum position of the hand in the initial and final positions are marked as the initial and final points of application of the PFA_S and PFA_E forces [5]. The total angle of rotation of the sequence ϕ_c can be written as the sum of the initial and final angles (13).

$$\phi_c = \phi_k - (-\phi_p) \tag{13}$$

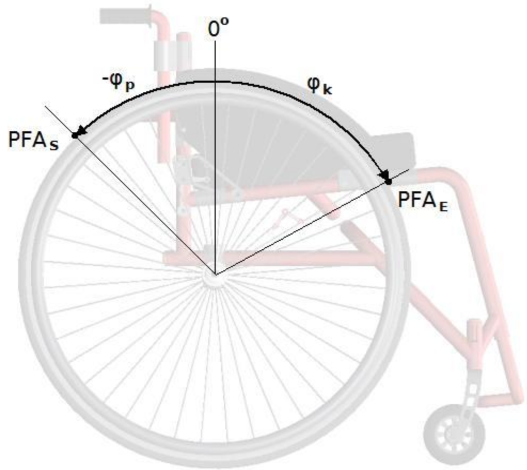

Fig. 5. – Diagram showing the angles $-\varphi_p$, φ_k, and the PFA_S start and PFA_E end points of the hand position

Assuming that the angle values for the lever drive will be denoted by the superscript $-\phi_p^*$, ϕ_k^* and ϕ_c^*, inequalities can be written that compare the lever drive with the pull drive in terms of the angle of rotation of the strings. Due to the shorter rotation arm of the strings relative to the lever, the total angle of rotation assumes the highest values for the traction drive $\phi_c > \phi_{c^*}$. In addition, the lever drive may not have a negative value of the initial angle $-\phi_p^*$, and if it does, it is much smaller than in the case of $| -\phi_c| >> | -\phi_p^*|$.

An important thing when selecting a wheelchair drive is to ensure that the user's body remains stable [15]. In many cases, paraplegics have a large part of the trunk muscles that are responsible for keeping the body upright. Such a disability makes it possible for the user to drive the wheelchair without any problems, but only forwards, i.e. generate the driving torque by pushing the driven element away. It becomes problematic to drive the wheelchair backwards because in this case the user has to pull the driven element towards himself. When pulling strings or levers as a result of an inert torso, the user's body leans forward instead of rotating the driven elements.

In order for the user not to fall off the wheelchair while driving the wheelchair, the driving force it generates must be balanced by friction forces and gravitational attraction forces. The figure (Fig. 6) shows the diagram of the forces acting on a person driving a wheelchair. As a result of generating the driving force F_{nap}, the center of gravity of the human body is affected by the reaction forces R_{xnap} and R_{ynap} (14, 15).

$$R_{nap}^{x} = -F_{nap}\cos(\alpha) \quad (14)$$

$$R_{nap}^{y} = F_{nap}\sin(\alpha) \quad (15)$$

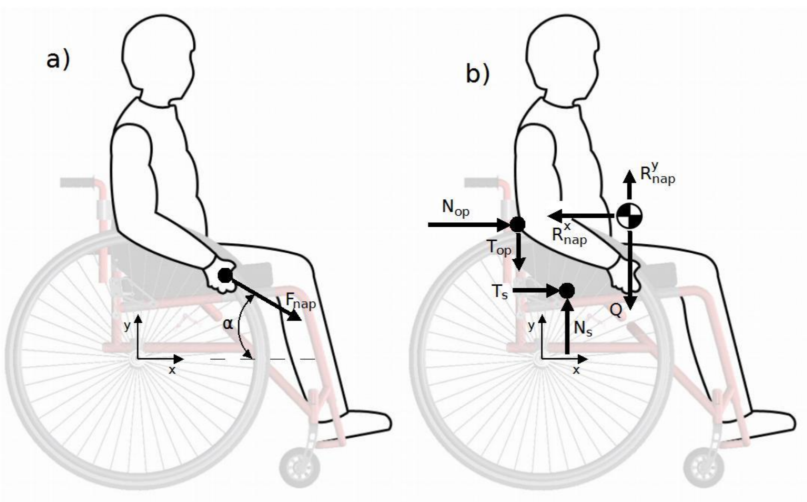

Fig. 6. – Diagram of the forces acting on the human body as a result of generating the driving force by the upper limb

It can be assumed that for the considered conditions, the seat and backrest are not deformable, which makes it impossible for the human body to slide backwards from the wheelchair and fall down under the influence of gravity. On this basis, it can be concluded that the reaction component of the driving force R_{xnap} is completely balanced by the reaction of the support N_{op}. This dependence causes the lack of movement of the lower limbs at the point of contact with the seat, which results in the friction force of the buttocks against the seat T_s being equal to 0. On this basis, it can be concluded that the user under the influence of the driving force F_{nap} delivered in such a way as in Fig. 6a) can only lift your body up along the y-axis. The force lifting the body up is the R_{ynap} component of the driving force, so that the user's body remains stable, it must be balanced by the force of the earth's attraction Q and the force of friction resistance of the back against the backrest T_{op} (16). On this basis, a simplified condition of maintaining body stability while propelling the wheelchair forward can be written (17).

$$T_{op} = \mu R_{nap}^{x} = \mu F_{nap}\cos(\alpha) \tag{16}$$

$$Q + T_{op} \geq R_{nap}^{y}$$
$$mg + \mu F_{nap}\cos(\alpha) \geq F_{nap}\sin(\alpha) \tag{17}$$

The limit value of the driving force F_{nap} at which the human body remains stable largely depends on the body mass m, the coefficient of friction between the back and the backrest μ and the driving force angle α.

4. Concepts of drives increasing the efficiency of manual wheelchair propulsion

In response to the above-mentioned problems resulting from driving a wheelchair, it is worth considering the introduction of gear drives to the standard equipment of traction drives, enabling the user to select the appropriate gear depending on the situation. The need for such a drive solution was also expressed by the T2RERC organization [16] located at the University of Buffalo. The answer to the need to use a traction drive with the ability to change gears may be a patent application for a multi-speed gear hub for manual wheelchairs [17] (Fig. 7).

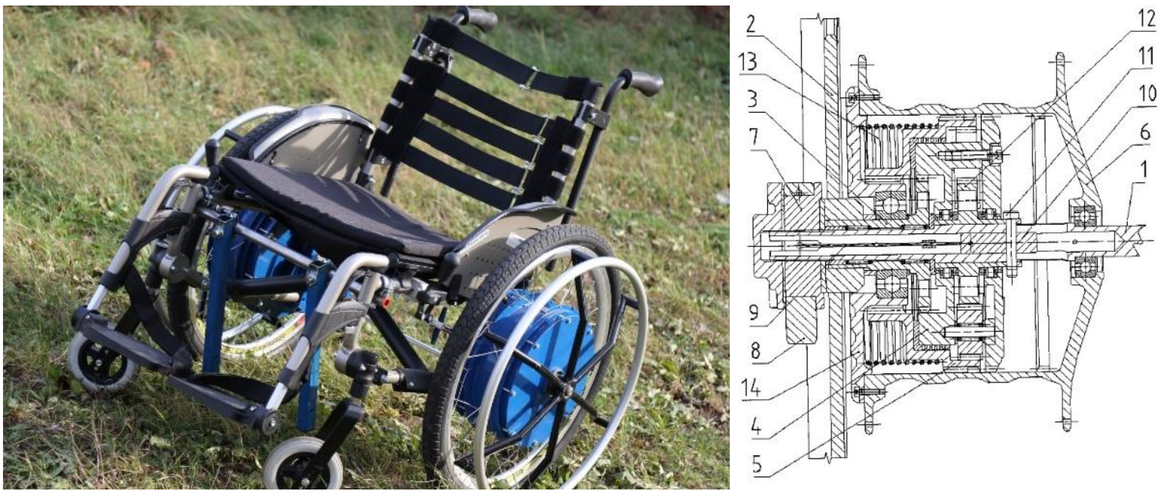

Fig. 7. – Multi-speed drive hub for tractive wheelchairs

The solution offers the user a discreet traction drive with three reduction gears for rough terrain and hill climbing, a 1:1 neutral gear for use in confined spaces or for leisurely driving, and a multiplication gear for fast travel on smooth terrain. As it was described earlier for a statistical wheelchair user, the problem is driving the wheelchair backwards with the use of traditional manual drives, during which there is a risk of the torso tilting forward.

A solution to this problem may be a patent application for a wheelchair lever drive system [18] (fig. 8). This solution is equipped with a gear transmission with a reversing gear, which, depending on the selected gear, allows the wheelchair to be driven forwards or backwards, while the user only pushes the levers away from himself. This drive works in a reduction ratio, which in combination with the levers makes it an ideal drive for driving in difficult terrain. An additional advantage of this mechanism is its lack of interference in the basic structure of the trolley, as well as easy and quick assembly and disassembly.

Fig. 8. – Wheelchair lever drive system

Conclusion

Based on the analysis, it was found that the operation of the manual drive system of the wheelchair is a biomechanically complex process. The essence of the manual wheelchair drive is its adaptation to the individual needs of the user. These needs result from the way the wheelchair is used and the degree of disability of the user. The constructions of manual drives existing on the market are archaic construction solutions characterized by simplicity and low cost of production. However, they do not fully meet the requirements of the wheelchair user. Therefore, it is necessary to start work on new design solutions for manual wheelchair drives. The research was carried out as part of the Lider VII project "research on the biomechanics of driving manual wheelchairs for innovative manual and hybrid drives" (LI-DER/7/0025/L-7/15/2016) financed by the National Center for Research and Development.

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Dynamic behaviour analysis in the impact mechanism

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Abstract: Dynamic processes in the mechanisms of shock action are investigated. The study is carried out using the contact-classical theory of impact, which combines classical dynamics with static solutions of the theory of elasticity. On this basis, the parameters of the shock pulse are determined: the maximum value of the impact force, the duration of the impact interaction, and the energy transfer coefficient. The obtained dependencies are used to calculate the shaking mechanisms of moulding machines in the foundry. The calculation method is quite general and has a wide range of applications. The results obtained allow us to evaluate the fatigue strength of the parts of the impact mechanism or calculate their durability.

Keywords: impact theory, impact mechanism, elastic element, dynamic process, momentum, impact force.

1. Introduction

Impact mechanisms are used in many machines in various industries: forging machines, stamping machines, shaking moulding mechanisms in mechanical engineering; machines for impact destruction of solid rock in mining, machines for driving piles in construction, etc. To calculate the parts and structural elements of impact machines, it is necessary to study the dynamic processes in impact mechanisms and determine the parameters of the impact pulse.

Due to the widespread use of shock and shock-vibration machines in the industry, the number of scientific papers on the theory and calculation of shock systems is growing every year. Several monographs [1] to [3] and many scientific articles [4] to [6] are devoted to the theoretical study of dynamic processes in shock systems. It should be noted that the vast majority of them are devoted to the theory of driving shock machines to provide the necessary energy and frequency of impact with the least cost [7], [8]. Due attention is also paid to the experimental study of the impact interaction of bodies [9]. At present, modern methods of experimental investigation of dynamic processes in shock systems have been developed based on electronic equipment [10].

Currently, depending on which bodies collide and at what speed, depending on the problem statement, different computational models of the impact system and different methods of analysis are used. For percussion mechanisms, they are most often applicable:

- model of a completely solid body;
- energy theory of impact;
- contact-classical shock theory;
- wave theory of impact.

Newton's theory of the impact of absolutely solid bodies allows us to find the velocities of bodies after the impact and the energy transfer coefficient during the impact or the impact momentum. This model is a convenient simplification for determining the kinematic parameters of the system. However, it has a significant drawback: the force of the impact and its duration remains uncertain.

The energy approach in the simplest interpretation allows you to find the maximum impact force but does not allow you to find the duration of the impact. This approach is quite applicable if the task is to evaluate the strength of structures or select design parameters from the strength condition. The impact is considered inelastic (without rebound) and the loss of energy, which has passed into heat and vibration, is neglected. Next, from the law of conservation of energy, we determine the coefficient of dynamism at impact, and through it, the maximum value of the impact force is determined.

To calculate the durability of parts and the maximum impact force, it is necessary to know the duration of the impact interaction. For this purpose, the contact-classical theory of impact is used. It combines classical dynamics with static solutions of the theory of elasticity, which allows in some cases to estimate quite accurately the impact force, deformation and duration of the impact. The criterion for the applicability of the contact-classical theory of impact is the ratio of the duration of the impact to the period of natural oscillations of the most extended body β. Calculations and experiments [2] show that at $\beta \geq 3$ it is permissible to consider colliding bodies as in classical mechanics and apply this theory of impact. Otherwise, the shock wave theory must be applied to calculate shock systems.

According to the wave theory, not the entire mass of the body is involved in the collision, but only the part of it that the shock wave has managed to propagate over the considered period [2], [11]. To write the equation of motion of a colliding surface, the theorem on the change in the amount of motion is used. When determining the parameters of the shock pulse at the common end, both direct and reflected shock waves are taken into account, that is, the shock pulse is formed during the impact interaction of the mechanism. This theory is applied to extended colliding bodies of the rod type (various impactors).

This work is devoted to the application of the contact-classical theory of impact to the analysis of dynamic processes in the shock system of shaking moulding machines.

2. Methods and solution of basic relations

To calculate the shock system, we apply the contact-classical theory of impact. In general, colliding bodies with masses m_1 and m_2 can move independently before the impact. In this case, the collision process is described by a system of equations:

$$m_1 \frac{d^2 x_1}{dt^2} = -N, \qquad m_2 \frac{d^2 x_2}{dt^2} = N, \qquad N = f(u),$$

where

- x_1, x_2 are the movements of the centre of gravity of colliding bodies;
- u is the total displacement (deformation) of the contacting surfaces.

The function N (force) is determined from the solution of the problem of elasticity theory about the deformation of contacting surfaces.

As a result of the study, it is necessary to find the kinematic characteristics of the movement, the maximum impact force, the duration of the impact and the energy transfer coefficient.

Next, we consider the collision of a rigid body with mass m moving at a velocity v_0 (Fig. 1, a) with a stationary deformable body (elastic element). The linear elastic-viscous model often provides sufficient accuracy (Fig. 1, b).

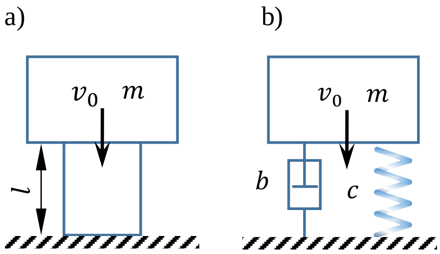

Fig. 1. - Design scheme of the impact system

Then the equation of motion will take the form:

$$m\ddot{x} = -N,$$

where

$$N = C\,x + b\dot{x}; \tag{1}$$

- c is the end stiffness of the elastic element;
- b is the ratio between the drag force and the moving speed.

The equation of motion is written in the following form

$$m\ddot{x} + b\dot{x} + \mathrm{c}x = 0. \tag{2}$$

The initial traffic conditions are as follows:

$$t = 0: \;\; x = 0, \;\; \dot{x} = v_0 = S/m,$$

where S is a shock pulse.

The solution of equation (2) under the accepted initial conditions has the form:

$$x = (\, v_0/p\,) \cdot e^{-\varepsilon t} \mathrm{sin} pt,$$

where $\omega_0 = \sqrt{c/m}$ is a natural frequency,
$\varepsilon = b/2m,\ \ n = \varepsilon/\omega_0,\ \ p = \omega_0\sqrt{1-n^2}$.

Further, we determine the speed of movement:

$$\dot{x} = v_0 e^{-\varepsilon t}\left(\cos pt - \frac{\varepsilon}{p}\sin pt\right).$$

Substituting the solution and the velocity of movement in the expression (1), we find the impact force

$$N = m v_0 \omega_0 e^{-\varepsilon t}\left(\frac{1-2n^2}{\sqrt{1-n^2}}\sin pt + 2n\cos pt\right). \tag{3}$$

Equating this expression to zero, we find the duration of the impact

$$\mathrm{tg}(pt_y) = -2n\sqrt{1-n^2}/(1-2n^2),$$

$$t_y = \left[\mathrm{arctg}(-2n\sqrt{1-n^2}/(1-2n^2)) + \pi\right]/p. \tag{4}$$

Then we find the maximum value of the impact force

$$dN/dt = mV_0\omega_0^2/p \cdot e^{-\varepsilon t}[p(1-4n^2)\cos pt - \varepsilon(3-4n^2)\sin pt].$$

Equating this expression to zero, we find

$$\mathrm{tg}(pt_m) = \sqrt{1-n^2}(1-4n^2)/n(3-4n^2),$$

$$t_m = \mathrm{arctg}\left[\sqrt{1-n^2}(1-4n^2)/n(3-4n^2)\right]\ /p.$$

Substituting this expression in (3), we find the maximum impact force

$$N_{\max} = S\omega_0\beta = m v_0 \omega_0 \beta, \tag{5}$$

$$\beta = 2n e^{-\varepsilon t_m}\left[\cos pt_m + \frac{(1-2n^2)}{2n\sqrt{1-n^2}}\cdot \sin pt_m\right].$$

The energy transferred to the elastic element is determined by

$$W = \int_0^{x_m} N dx = \int_0^{t_y} N\dot{x}\, dt.$$

Taking into account the expressions of integrand functions, we can write

$$W = \frac{S^2\omega_0}{m(1-n^2)}\int_0^{t_y} e^{-2\varepsilon t}\left[(1-2n^2)\text{sin}pt + 2n\sqrt{1-n^2}\text{cos}pt\right]\left(\sqrt{1-n^2}\text{cos}pt - n\text{sin}pt\right)dt.$$

Added symbols:

$$pt = \theta,\ pt_y = \theta_0,\ a = 2n/\sqrt{1-n^2}.$$

Then the last expression after the conversion will take the form

$$W = \frac{S^2}{m(1-n^2)}\int_0^{\theta_0} e^{-a\theta}\left[n(1-n^2)\text{cos}^2\theta - 0{,}5a(1-2n^2)\text{sin}^2\theta + 0{,}5(1-4n^2)\text{sin}2\theta\right]d\theta.$$

After integration, we obtain

$$W = \frac{S^2}{2m}\left[1 + e^{-a\theta_0}\left(\frac{1-2n^2}{1-n^2}\text{sin}^2\theta_0 + 0{,}5n\text{sin}2\theta_0 - 1\right)\right]. \quad (6)$$

Energy transfer coefficient

$$\eta = W/A_0,$$

Impact energy

$$A_0 = mv_0^2/2 = S^2/2m.$$

Taking into account the trigonometric formulas and the expression (4), we have

$$\text{sin}^2\theta_0 = \text{tg}^2pt_y/\left(1+\text{tg}^2pt_y\right) = 4n^2(1-n^2),$$

$$\text{sin}2\theta_0 = 2\text{tg}^2pt_y/\left(1+\text{tg}^2pt_y\right) = -4n\sqrt{1-n^2}(1-2n^2).$$

Now we finally get

$$\eta = 1 - e^{-a\theta_0}. \quad (7)$$

The rebound coefficient is usually determined experimentally. We find the relation of this coefficient to the attenuation coefficient n. The bounced body has kinetic energy

$$mv_{re}^2/2 = A_0 - W,$$

where

$$v_{re} = kv_0, W = \eta A_0.$$

Then

$$k = \sqrt{1 - \eta}. \tag{8}$$

Given the expression (7) we have

$$k = e^{-a\theta_0/2} = \exp(-n\theta_0/\sqrt{1-n^2}),$$

$$\theta_0 = \mathrm{arctg}(\,-2n\sqrt{1-n^2}/(1-2n^2)\,) + \pi.$$

For a known value of the coefficient k, this formula can be used to find the parameter n. The graph of the relationship between these parameters is shown in Figure 2.

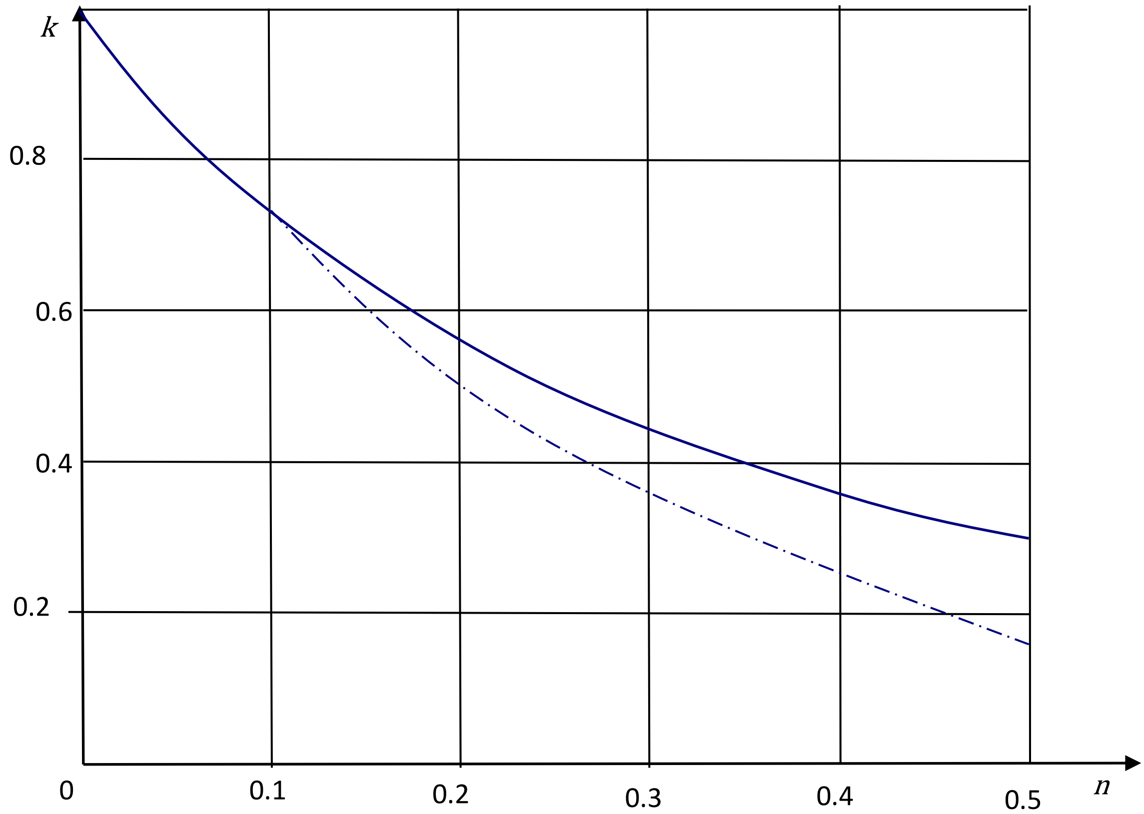

Fig. 2. - Graph of the function between the rebound coefficient and the attenuation coefficient

Knowing the parameter n by formulas (4), (5), we can find the duration of the impact and the coefficient β, to determine the maximum impact force. These data will be used for strength calculations.

If we assume that the stroke ends at $x = 0$, then these dependencies are simplified:

$$t_y = P/\pi;$$

$$k = \exp\left(-\frac{\pi n}{\sqrt{1-n^2}}\right) \quad \text{or} \quad n = \frac{\ln k}{\sqrt{\pi^2 + \ln^2 k}}$$

The graph of the relation between the coefficients n and k, calculated using this formula, is also shown in Figure 2 with a dotted line.

The rebound coefficient for the most commonly used materials in shock systems varies within the range of 0.4 – 0.7 [12]. $k = 0.55$ was obtained experimentally for the collision of steel structures.

In some cases, non-linear shock absorbers are used to soften the impact. In this case, the force in expression (1) depends non-linearly on the displacement and/or velocity [13]. Then the equation of motion (2) will be nonlinear and its solution has a more complex form or does not have an analytical expression at all [14]. Herewith, the method of calculating the shock system remains the same, only the type of calculated dependencies becomes more complicated.

3. Results

Note that for most of the existing structures of the shaking mechanisms of forming machines, the condition of applicability of the contact-classical theory of impact is fulfilled.

For mechanisms with shock absorption, the stiffness of the system is equal to the stiffness of the shock absorber springs, and the mass and velocity are

$$m = m_1 + m_2, \ \ v_0 = (m_1 U_1 + m_2 U_2)/m.$$

The shaking mechanism with a hard impact is considered, the design scheme is shown in Figure 3. We take the following geometric parameters of the shaking cylinder:

$$l = 25\text{cm}, \ D = 0.35\text{m}, \ d = 0.2\text{m}.$$

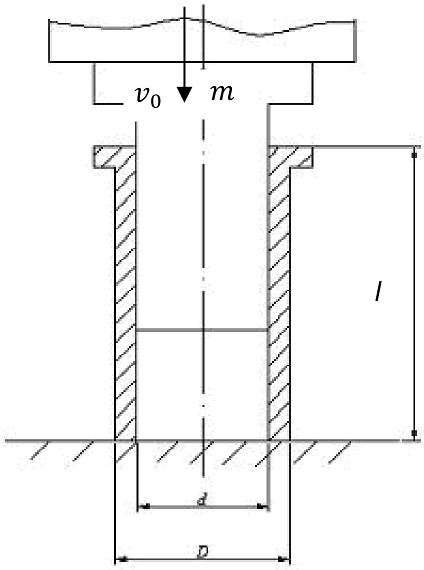

Fig. 3. - Design scheme of the shaking mechanism with a hard impact

The mass of the moving parts (the shaking piston and the table with the loaded flask) is assumed to be 683 kg. The speed at the moment of impact is taken from the calculation of the indicator diagram with a hard impact $v_0 = 0.916\ \text{m/s}$. Determine the stiffness of the local deformation:

$$A = \pi(D^2 - d^2)/4 = 6{,}48 \cdot 10^{-2}\text{m}^2,$$

$$c = EA/l = 2 \cdot 10^{11} \cdot 6{,}48 \cdot 10^{-2}/0{,}25 = 5{,}184 \cdot 10^{10}\text{N/m}.$$

First, we will determine the maximum force from the energy balance. If the impact velocity is known, then the dynamic coefficient can be determined by the formula

$$k_d = 1 + v_0/\sqrt{g\delta_{st}},$$

where the static displacement of the impact point in our case is determined by the formula

$$\delta_{st} = \frac{Ql}{EA} = \frac{683 \cdot 9.8 \cdot 0.25}{2 \cdot 10^8 \cdot 6.48 \cdot 10^{-2}} = 0.13 \cdot 10^{-6}\text{м}.$$

Then the maximum impact force is defined as:

$$k_d = 1 + 0.916/10^{-3}\sqrt{9.8 \cdot 0.13} = 812; \quad N_{\max} = Qk_d = 6693 \cdot 812 = 54.4 \cdot 10^5\text{N}.$$

Now, for the calculation, we apply the contact-classical theory. The rebound coefficient k is assumed to be equal to 0.4. Then, according to the graph in Figure 2, we find n=0.35.

Natural frequency is

$$\omega_0 = \sqrt{c/m} = \sqrt{5.184 \cdot 10^{10}/683} = 0.86 \cdot 10^4\text{s}^{-1},$$

and parameter is

$$p = 0.86 \cdot 10^4 \cdot 0.937 = 0.806 \cdot 10^4 \text{ s}^{-1}.$$

Using the above formulas, we find:

$$pt_m = \text{arctg}[0.937(1 - 4 \cdot 0.35^2)/0.35 \cdot (3 - 4 \cdot 0.35^2)] = \text{arctg}0.544 = 0.496,$$

$$t_m = 0.615 \cdot 10^{-4} \text{ s}; \quad \omega_0 t_m = 0.496/0.937 = 0.529.$$

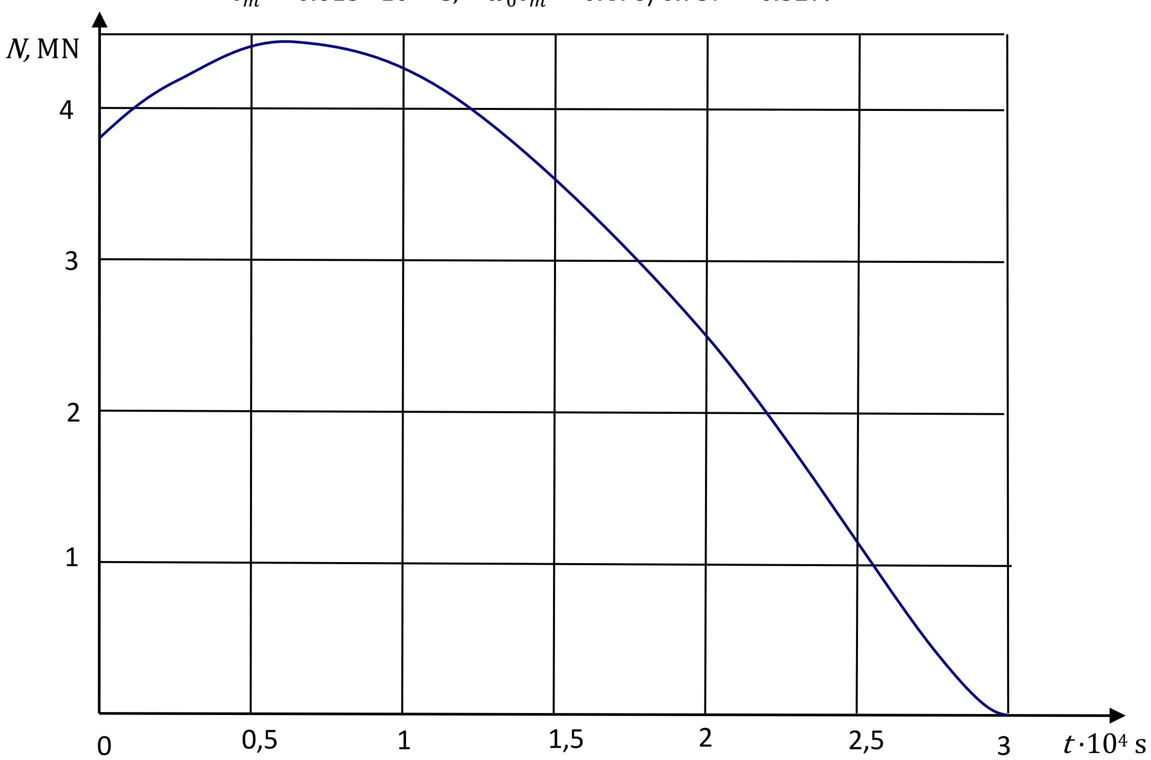

Fig. 4. - Graph of the impact force change

Substituting everything into formula (5), we find:

$$\beta = 0.7\exp(-0.35 \cdot 0.529)\left(\cos0.496 + \frac{1 - 2 \cdot 0.35^2}{0.7 \cdot 0.937}\sin0.496\right) = 0.83;$$

$$N_{\max} = \omega_0 \beta m v_0 = 0.86 \cdot 10^4 \cdot 0.83 \cdot 683 \cdot 0.916 = 44.7 \cdot 10^5\text{N}.$$

This value differs from the value obtained above according to the energy theory of impact by 21.7 %. A noticeable refinement of the calculation results is associated with taking into account the forces of viscous resistance during the deformation of the elastic element.

The duration of the impact is found by the formula (4):

$$t_y = \frac{1}{0.806 \cdot 10^4}\left[\mathrm{arctg}\left(-\frac{0.7 \cdot 0.937}{1 - 2 \cdot 0.35^2}\right) + \pi\right] = 3 \cdot 10^{-4}\mathrm{s}.$$

The graph of the change in the impact force calculated by the formula (3) is shown in Figure 4. We find the energy transfer coefficient to the elastic element by the formula (7):

$$a\theta_0 = 2npt_y/\sqrt{1 - n^2} = 0.7 \cdot 0.806 \cdot 10^{-4} \cdot 3 \cdot 10^{-4}/0.937 = 0.82,$$

$$\eta = 1 - \mathrm{e}^{-0.82} = 0.84.$$

The same result can be obtained by the formula (8).

Knowing the maximum force and duration of the impact, as well as the number of impacts per second, which is determined when calculating the indicator diagram, you can estimate the fatigue strength or durability of the shaking cylinder.

Conclusion

Based on the results of the work, the following conclusions can be drawn:

- by combining the methods of classical dynamics with static solutions of the theory of elasticity, a contact-classical theory of impact is proposed, which gives more accurate results and wider calculation possibilities than the currently used energy theory of impact;
- the main relations for the dynamic calculation of shock mechanisms are obtained;
- these dependencies are used to determine the parameters of the shock pulse and the energy transfer coefficient in the shaking mechanisms of moulding machines.
- the results obtained allow us to evaluate the fatigue strength of the parts of the impact mechanism or calculate their durability.

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Features of Magnetic Field Modeling for Magnetic-Abrasive Treatment of Complex-Profile Surfaces

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Abstract. The process of modeling a magnetic field under magnetic abrasive machining of complex surfaces of engineering products is considered. Spherical shapes and surfaces of small-modular gears are considered as complex-profile surfaces. The intensity and magnetic induction of the magnetic field are determined, by which the effectiveness of the magnetic abrasive processing method is evaluated. The optimal values of the angle α in the processing zone have been identified, affecting the surface quality of the products with the magnetic abrasive processing method. The results of the dependence of the relative induction β on the value of the angle α are presented.

Keywords: magnetic abrasive machining, ferro-abrasive powder, surface, quality, magnetic induction, hardness.

Introduction

One of the most common forms of composite surfaces is a spherical shape. It is known that the technology of finishing spherical parts, in particular finishing, is based on the contact interaction of the tool and the part by their mutual wear. The kinematics of the process consists in the simultaneous rotation of the leading link in the form of a part and the driven link or lapping elastically pressed against it through a ball joint. In this case, the lapping axis passes through the axis of rotation of the part and is inclined to the axis of the formed sphere at a certain angle [1]. This process is characterized by the complexity of the mutual influence of the main technological factors, which are amenable only to indirect control.

The complexity of processing such a surface is due to the lack of guaranteed three-axis rotation of the parts, which does not make it possible to obtain a high percentage of uniformity of surface treatment. Other problems are the variability of the free rotation speed of the tool, the high gradient of the cutting speed vector and the uneven contact pressure between the tool and the part due to the presence of so-called loops and return points of the trajectory. The result of this effect is the absence of the same thickness of the removed allowance, which leads to a decrease in quality and accuracy. This problem can be solved by using magnetic abrasive treatment (MAO) of the surface, where a change in the magnitude and direction of the magnetic flux in the processing zone creates a magnetic field that changes the position of the axis of rotation of the ball and informs the ferroabrasive tool planetary motion around the product [2]. This ensures the uniformity of metal removal and the accuracy of the geometric shape of the workpiece.

1. Research methods

The calculation of the electromagnetic field in any electrical device is determined by the shape of the surface that separates media with different physical and mechanical characteristics in the field of its existence. The complexity increases when it is necessary to take into account the nonlinearity of the media, depending on the values characterizing the electromagnetic field such as the magnetic permeability of the medium and the field strength. With MAO, the movement of media, i.e. the tool and the ball, should also be added. Therefore, it is necessary to present calculations of electromagnetic field studies in an analytical form. It is known that there is a certain feature of the calculation associated with the physical modeling of the field and consisting in the implementation of the assumption condition. An example of this is that the displacement current inside the conductors can be neglected, unlike the conduction current. The expediency of choosing a coordinate system, since the differential equations for vector quantities H and B also depend on time, is determined by the nature of the problem. This is due to the minimization of funds and costs for solving extremely complex boundary-value problems. Another problem in choosing a determinant is the identification of the sign when considering the increment or decrease of the function on elementary sites. However, the need to get an idea of the MAO process of spherical surfaces requires the establishment of a research method and a model in which the phenomena are completely or mostly of the same physical nature as the original. This greatly facilitates obtaining the necessary results due to the choice of the most acceptable ranges of changes in the physical quantities and geometric dimensions of the machined parts.

A sample for physical modeling is a sphere rotating with a frequency of n and located in a magnetic field. The task is to determine the magnetic field strength, considering the field on the axis of the circular current to be known, by its direct integration.

The magnetic field strength on the axis of rotation at the point M (Figure 1), due to the current dI, is equal to:

$$dH = dH_z = dI\frac{\sin^3\beta}{2r}.$$

According to Figure 1, the relations follow:

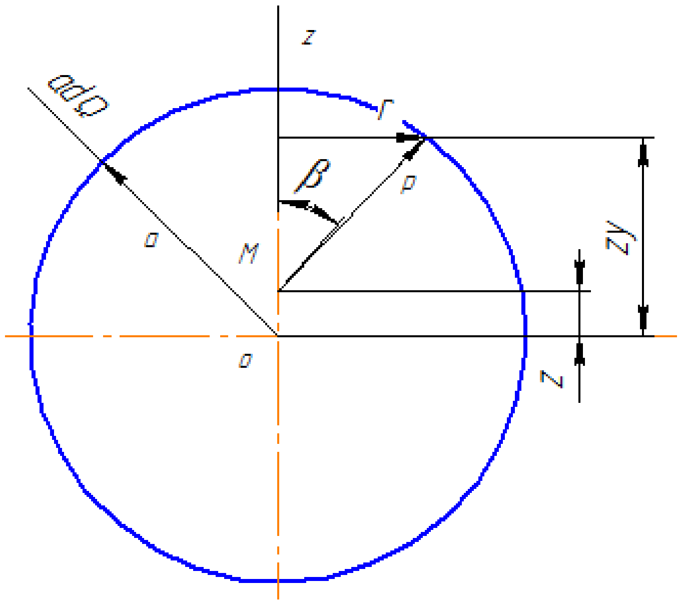
$$\sin\beta = \frac{r}{\rho};\quad r^2 = a^2 - z^2;\quad \rho^2 = z^2 + a^2 - z_э z.$$

Therefore, $d\theta = -\frac{dz_э}{z}$ and $z_э dz = -\rho\cdot d\rho,$

$$d = \frac{-\rho^4 + 2\rho^2(z^2+a^2)-(a^2-z^2)}{\rho^2}dS.$$

Substituting these values into expressions for dH, we get:

$$d = -\frac{I}{16az^3}\cdot\frac{\rho^4 + 2\rho^2(z^2+a^2)-(a^2-z^2)}{\rho^2}dS.$$



z - is the distance from the center of the ball to the point of determining the intensity of MF, m; *a* - is the radius of the ball, m; *β* - is the angle between the Z axis at the point of determining the intensity of MF

Fig. 1. - Diagram for determining the magnetic field strength when using MAP

Integrating this expression by ρ, we get:

$$H = -\frac{I}{16az^3} \cdot \left[\frac{\rho^3}{3} - 2(z^2 + a^2)\rho - (a^2 - z^2)\frac{1}{\rho} \right].$$

The field outside the sphere defining the z coordinate, which varies from $-\infty$ to $-a$ and from a to $+\infty$, is found as:

$$H = \frac{Ia^2}{3z^3}.$$

3. Results and discussion

Thus, analyzing the obtained expression, we can conclude that the most optimal range of processed ball sizes are diameters of 2-10 mm. This is due to the fact that the required magnitude of the magnetic field strength at MAP is represented by a numerical value equal to 100-500 $A \cdot m^{-1}$. The maximum theoretically possible for MAP is the size of the ball d = 15 mm.

Another common form of complex-profile surfaces is the surface of small-modulus gears, one of the methods of obtaining which is cold rolling, providing an accurate tooth profile [3,4].

During the rolling process, the processed gear wheel and the knurling tool, which has the shape of a cylindrical gear wheel, are in a non–locking engagement. As a result of the relative sliding of the profiles of the teeth of the workpiece and the tool on opposite sides of the wheel tooth, the allowance material flows in different directions. On the driven side of the wheel tooth profile, the metal moves from the head and leg of the tooth to the dividing circle. As a result, the metal is covered on the dividing circle – a protrusion is formed. On the opposite side of the tooth profile, the metal moves from the dividing circle to the head and leg of the tooth, which is why a depression appears in the zone of the dividing circle. Due to the flow of metal towards the tooth head, the outer diameter of the processed wheel increases (a horn-shaped growth is formed). The different nature of deformations and metal flows on both sides of the teeth create difficulties in obtaining a symmetrical profile of the wheel tooth. In order to obtain satisfactory results, a different correction is introduced on each side of the knurler tooth, but it is impossible to completely eliminate the horn-shaped influx.

In practice, the optimal way to solve this problem is grinding along the outer diameter of the gear wheel after quenching. As a result of grinding, a lot of burrs and burns are formed, which requires subsequent finishing. To date, for this purpose, the following are used: lapping, tooth honing, electrochemical treatment. However, these methods have a number of characteristic disadvantages. These include: high duration of the processing process, low tool life, environmental harmfulness of production, constant installation and dismantling of the lapping system (drive, relative location), frequent lapping mass, the need for disposal of spent abrasive, high qualification of the worker and the cost of the tool.

The removal of metal at MAP is carried out as a result of the force action of the powder on the surface of the part and the specified relative movements. The processed part 1 is placed between the pole tips 2 of the electromagnetic system with an established gap δ, in which the FAP is fed (Figure 2).

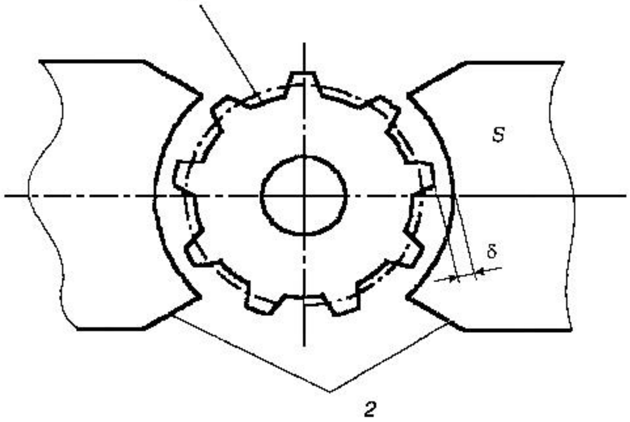


Fig.2. - Diagram of magnetic abrasive treatment of gears

For a discontinuous surface, the distribution of the magnetic flux is largely in the nature of uncertainty. This is due to the desire of the magnetic flux to carry out its passage through an energetically advantageous section of the magnetic circuit. The problem of the MAP of gears is the complexity of processing the variable diameter of the circles of their protrusions and depressions. This is due to the fact that as you move away from a conductor with a current around which, according to Ampere's law, there is a field, the latter weakens. A drop in the field strength, which is its power characteristic, leads, respectively, to a decrease in the pressure of the ferroabrasive powder (FAP) on the treated surface, and ultimately to a decrease in the removal of the material. In connection with the above, the problem arises of the optimal application of this method in order to fully utilize the technological capabilities of MAP. As mentioned above, it is the presence of a module $m \leq 2.5$ mm that practically limits the finishing treatment of gears by the tooth-honing method, and according to the data, the magnetic field penetrating into the groove attenuates at a depth approximately equal to its width. Consequently, the smaller the gear module, the more efficient the process of removing the material of the processed product is, despite the variability of the diameters of the protrusions and depressions when using MAP [5]. In addition, a positive factor in this process is the presence of an involute profile of the tooth contour (it can be conditionally considered trapezoidal), which increases the efficiency of FAP access to the treatment area and improves its quality. The second important condition is that the sharp edge is a magnetic flux concentrator and it is here that the greatest density of this flux will be.

The most preferable is the mathematical way of solving the problem. This gives general formulas for calculating the magnetic field in the processing zone and the possibility of obtaining a picture of this field, which leads to an assessment of the potential of the MAP process [6, 7]. This study is carried out in the area between the surfaces of the EMS (electromagnetic system) pole and the gear surface of the Z-plane wheel. It can be represented as a quadrilateral ABCD (Figure 3).

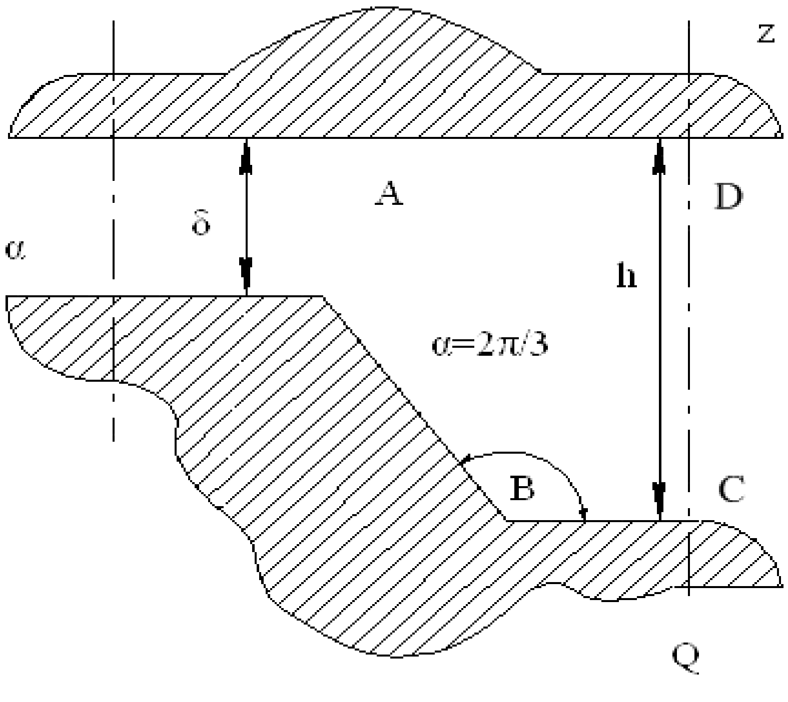


Fig.3. - The working area of the gear contour of the wheel at MAO with the condition α=2π/3

The mapping of this quadrilateral to the half-plane Q using the Christoffel-Schwartz integral in general looks like this:

$$Q = C \int_{Q_0}^{Q} (Q-a)^{\alpha_1 - 1}(Q-b)^{\alpha_2 - 1}(Q-c)^{\alpha_3 - 1}(Q-d)^{\alpha_4 - 1} + C_1,$$

where a, b, c, d are the coordinates of the vertices of the quadrilateral ABCD;

C, C1,Q_0 are arbitrary constants;

α1, α2, α3, α4 are angles at the vertices of the quadrilateral ABCD (in fractions of π).

The solution of this case after a number of transformations has the form:

$$\frac{P}{2\delta}=\frac{1}{\delta}\left\{\begin{array}{c}\ln(1-\beta)-\alpha\ln(\alpha\beta-1)+\\ +\frac{1}{2}\left[\begin{array}{l}\alpha\ln(1+\alpha\beta+\alpha^2\beta^2)-\\ -\ln(1+\beta+\beta^2)\end{array}\right]+\\ +\sqrt{3}\cdot\left(\operatorname{arctg}\frac{2+\alpha\beta}{\sqrt{3}\alpha\beta}-\operatorname{arctg}\frac{2+\alpha\beta}{\sqrt{3}\beta}\right)\end{array}\right\}+\frac{\sqrt{3}}{2}(1-\alpha),$$

where P - is the gear pitch, mm;

δ - is the gap between the EMC pole and the diameter of the gear tops, mm;

h - is the depth of the groove, mm.

It follows from expression (8) that the minimum value of relative induction:

$$\beta=\frac{B}{B_{\max}}=\sqrt[3]{\frac{Q+1}{Q+\alpha^3}},$$

$$\beta=\frac{1}{\alpha}.$$

For h = 0 (smooth cylindrical surface), β = 1, and if h ≠ 0, then the dependence βmin = f(α) has the form of a hyperbola. By setting the values of the relative induction β and substituting them into the equation, the corresponding values of P/2δ are revealed for different β. By presenting these indicators in relation to a real gear wheel (diameters of the circumference of vertices and depressions, the engagement modulus, etc.) and a magnetic field (magnetic induction), it is possible to determine the most acceptable processing conditions and establish the capabilities of the MAP process to obtain the necessary qualities and performance [8]. Figure 4 shows the dependence $\beta = f\left(\frac{P}{2\delta}\right)$ at a value of α = 120° (trapezoidal tooth), which most corresponds to the shape of the working contour of the gear wheel.

The conducted studies allowed us to determine that the maximum possible value of *α*, at which the MAP process is carried out, is the range 4-6. By converting *P/2δ* as *πm/2δ* and substituting this range, it is possible, by varying the indicators *m* and *δ*, to predict the processing of small-module gears by the MAP method.

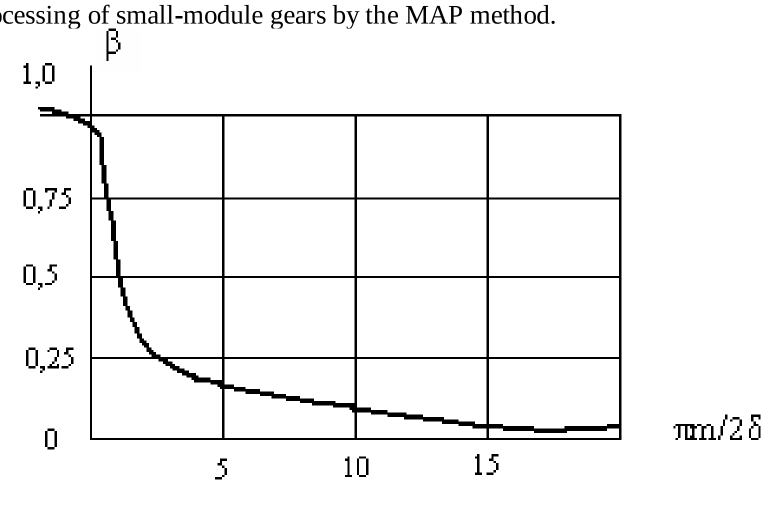


Fig. 4. - Distribution of relative induction β in the groove of the gear wheel at α=2π/3

Conclusion

Based on the above, studies were conducted aimed at assessing the technological capabilities of the MAP method in the processing of small-module wheels (m = 1.5 mm). Gears had an oblique tooth, β = 12º, material – steel 40X GOST 4543-71, 40-45 HRC, equipment – SFT 2.150.00.00.000, FAP – 15 CT TU 6-09-03-483-81. Parameters and processing modes: magnetic induction value, B = 1 Tl; cutting speed, V_c = 0.15 m/s; oscillation amplitude, A=1.5 mm; working gap filling factor, K_f=1; working gap value, δ=1 mm. The main task of processing by the MAP method was to round the chamfers of the toothed contour of the wheels and eliminate the burrs formed by the previous grinding operation along the outer diameter of the parts.

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Lean production at machine-building enterprises of the Republic of Kazakhstan

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Abstract. Lean manufacturing is a specific management concept designed to constantly look for opportunities to eliminate waste in production. The results that can be achieved by introducing lean production at enterprises are given. A model of lean manufacturing has been developed, covering losses ranging from excess inventory to control inefficiency. A tripartite graph of the relationship between types of losses, their causes and methods of elimination is described. Losses, causes and methods for their elimination at the stage of acceptance of raw materials, transportation and storage of materials, distribution of materials, production of products using rank estimates are given.

Keywords: lean manufacturing, tools, model, losses

Introduction

In the current conditions of economic development for Kazakhstani machine-building enterprises, it is especially important to solve the problems of rational use of production resources. The introduction of resource-saving technologies is the basis for a dynamic increase in the competitiveness of enterprises in the industry, and, as a result, the sustainable development of the national economic complex of the country and economic growth [1].

One of the main factors for ensuring a high level of efficiency is the successful implementation and use of lean production methods (Lean Production) [2, 3]. However, in the literature, the concept of Lean is presented in a significantly simplified form and often does not correspond well to the realities that managers and consultants face on implementation projects.

The lean manufacturing model is the optimal way to manage any manufacturing enterprise [4]. Manufacturers that continue to rely on existing planning models in an effort to reduce wait times, reduce working capital costs, and improve quality risk losing market share to competitors who have moved to lean manufacturing [5]. Although the path to successful resolution of internal problems in the implementation of the transformation can be difficult, but the transition to lean manufacturing will serve the interests of the company and justify the efforts expended on it [6].

In this regard, the purpose of these studies was to create a lean production model using the example of Maker LLP, taking into account the identification of the main losses in production, lean production tools.

1. **Research methods**

As research methods, methods of synthesis and analysis of information, data combinatorics when constructing a graph of losses, the causes of their occurrence and ways to eliminate them, as well as statistical analysis and methods of group examination, were used.

When creating a lean manufacturing model, the main function is the resource saving function, which allows you to accelerate the growth rate of production, reduce prices for engineering products, achieve high final economic results, and solve social and environmental problems [7].

The choice of one or another mechanism for saving resources within the framework of the activity of a machine-building enterprise is determined by the level of intra-production division of labor, the type of production, the degree of mechanization and automation of individual processes.

Therefore, when creating a resource-oriented lean manufacturing model, special attention is paid to the extent to which its results will allow:

- increase the yield of finished products from a unit of raw materials;
- reduce the consumption of materials per unit of finished product;
- reduce waste and production losses;
- to optimize the system of motivation of workers for the rational use of raw materials and materials.

2. Results and discussion

The studies carried out by both domestic [8 - 10] and foreign specialists [11 - 13], published in the press, do not fully reflect the problem of the implementation and operation of the resource-saving process management system as a tool for increasing production efficiency. In this regard, further research focused on the latest achievements in science and technology, in the field of resource management, is extremely relevant. It is necessary to further comprehensive and in-depth study of the links in the mechanism of resource conservation management and conduct research in this direction.

The presence of the above problems has caused the need to search for and develop fundamentally new scientific provisions aimed at improving the efficiency of resource consumption by machine-building enterprises. Currently, the use of existing traditional methods of organizing production is becoming insufficient. At the forefront is the growing desire to avoid residual materials and to make the most of production waste, which cannot be avoided. In accordance with this, a search is underway for concepts, methods and models that allow, along with reducing environmental impacts, to help reduce the costs of the enterprise.

One of the directions for solving the problem is an integrated approach to managing resource conservation as a process related to product quality management, transportation and storage, as well as ecology, since the source of all resources, including material ones, is nature.

Solving the problem of resource saving management is directly related to the no less urgent task of improving the quality of products of machine-building enterprises.

Firstly, improving the quality of products is one of the reserves for saving resources in the sphere of its consumption, thanks to the optimization of consumer properties.

Secondly, product quality is generally characterized by the ability to implement its main functions. Functional quality indicators characterizing suitability for purpose are criteria for assessing all types of costs, since their ratio determines the efficiency of created and operated products. This imposes restrictions on the choice of rational resource-saving engineering solutions taken in relation to the design at the development stage.

The implementation of this approach at the design stage determines the labor, material and energy costs in the process of production, operation, maintenance and restoration of performance during maintenance and repair. In this regard, decisions should be made on the issues of rational use of resources, focusing on providing product reliability indicators that characterize its reliability, maintainability, persistence of properties and durability. It is necessary to take into account the direct relationship between reliability indicators and resource saving, since a low level of reliability indicators can increase the cost of material resources during product operation.

Ergonomic and aesthetic properties of products are associated with the search for the optimal combination of forms and technologically rational design, which determines the solution of resource saving problems.

The factors that determine the transportability of products significantly affect the costs of labor, material and energy under given conditions for the execution of work at all stages of the manifestation of these costs, which also affects the solution of issues of saving resources.

The level of harmful effects of engineering enterprises and their products on the environment, arising in the process of production, operation and repair, depends on the engineering solutions adopted in the development of the design, technological solutions in the manufacture of products, as well as the volume of investments in fixed assets aimed at environmental management and rational use of natural resources.

The decisions made affect the costs of all types of resources at different stages of the manifestation of product properties, therefore, ensuring resource conservation should be considered as a complex task of producing high quality products requiring a lean manufacturing model.

The lean manufacturing model should cover all stages of the production process and take into account losses, which include:

- excess stocks;
- unnecessary movements;
- unnecessary transportation or movement of objects;
- deviations in quality, cost and timing of the programs;
- waiting or delays (idle of people or storage of materials);
- production in excess of the program or underproduction;
- inefficient setup;
- ineffective control.

All of these losses reduce or lead to a complete loss of competitiveness. The lean production model offers a solution to the problems of rational use of resources through the application of a system of methods and techniques to prevent these types of losses.

To describe the relationship between the causes of losses N, losses P and methods and tools M, you can use a tripartite graph (Figure 1).

Let N = {n1, n2, n3, n4, n5, n6, n7, n8, n9, n10, n11, n12, n13} be the set of loss causes, where:

n1 - long changeovers;

n2 - imperfection of the planning system for production and supply of materials;

n3 - large batches of manufactured products;

n4 - proactive production;

n5 - redundant equipment;

n6 - unstable quality;

n7 - inefficient organization of jobs;

n8 - irrational placement of equipment, production sites;
n9 - lack of understanding of consumer requirements;
n10 - imperfection of technologies;
n11 - technology violation;
n12 - low qualification of workers;
n13 - inappropriate tools, equipment, materials.

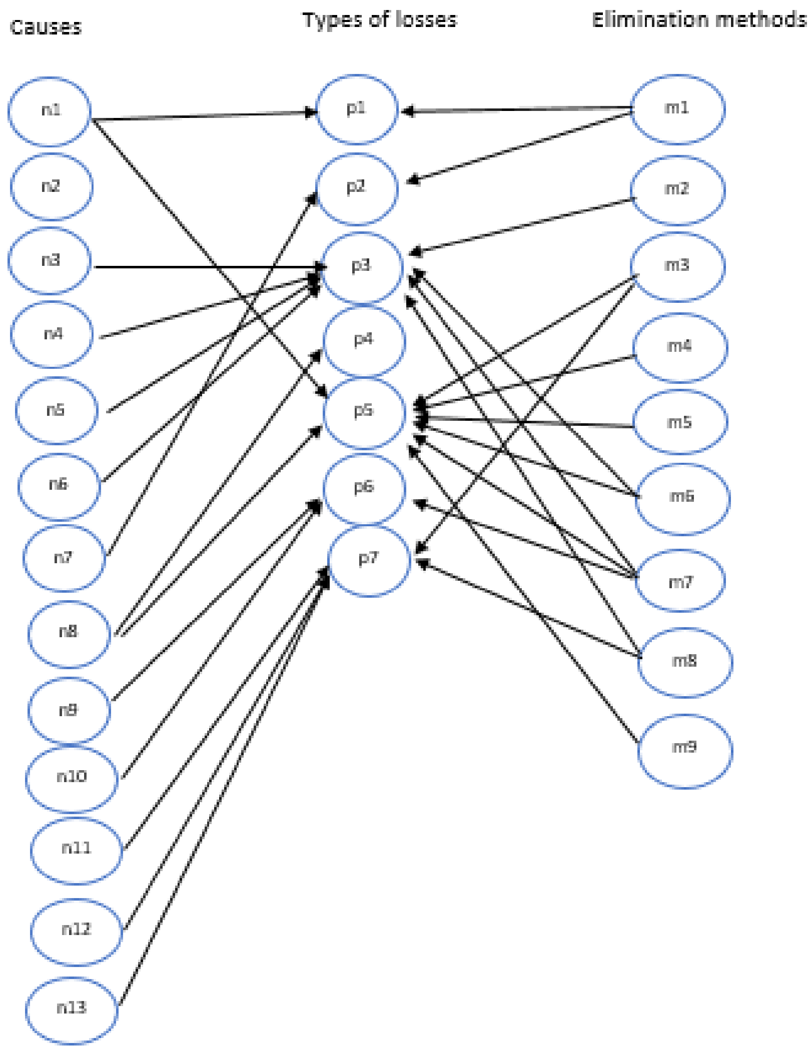

Fig. 1. - Tripartite graph of the relationship between types of losses, their causes and methods of elimination

P = {p1, p2, p3, p4, p5, p6, p7} – set of loss types, where:
p1 - excess reserves;
p2 - unnecessary movements, movements;
p3 - overproduction;
p4 - unnecessary transportation;
p5 - expectations;
p6 - excessive processing;
p7 - defects.
M = {m1, m2, m3, m4, m5, m6, m7, m8, m9} – a set of loss elimination methods and tools, where:
m1 – 5S system;
m2 - Kanban;
m3 - TPM (Total Equipment Maintenance);

m4 - SMED (quick equipment changeover);
m5 - kaizen;
m6 - just in time;
m7 - SWIP improvement program;
m8 - Poka Yoke (protection against unintentional violations);
m9 - TFM (Total Flow Control).

For example, we can cite the data of the company "Maker" LLP, engaged in the manufacture and repair of mining equipment.

Table 1 shows the losses, causes and methods for their elimination at the stages of acceptance of raw materials in the production of hydraulic pumps.

Table 1. Losses, causes and methods for their elimination at the stage of acceptance of raw materials

Loss	Cause	Cause Rank	Elimination Methods
Overproduction	Irregular mode of supply of raw materials	3	Multiple Supplier Selection
Excessive movement	Raw material release rate for control	4	Equip a site for receiving raw materials
	Stockpiling	4	Stock forecasting
	Drag parts for repairs	4	-
Transportation	Transfer from car to stock	4	-
Downtime and waiting	Lack of raw materials	1	Conclusion of contracts in accordance with the plan for the supply of raw materials
Defects and alteration	Impact on unloading	3	Conduct additional training. Work with suppliers to equip machines
	Chips, scuffs	3	Conduct additional training

Table 1 shows that when accepting raw materials at the enterprise, six types of losses can be traced: overproduction, excessive movements, losses during transportation, equipment downtime, defects, and rework. All types of losses were assigned a rank based on group expertise: 0 – immediately; 1 - urgent, important; 2 - urgent, unimportant; 3 - important, not urgent; 4 - not important, not urgent.

The most dangerous losses are downtime and waiting due to lack of raw materials. As a method of eliminating these losses, it is proposed to conclude contracts in accordance with the plan for the supply of raw materials.

Table 2 shows the losses at the stage of transportation and storage of materials.

Table 2. Losses, causes and methods for their elimination at the stage of transportation and storage of materials

Loss	Cause	Cause Rank	Elimination Methods
Defects and alteration	Correction of metal on site	4	Modernize the site
	Defect rearrangement	4	-
Transportation	Rearrangement	4	Use slings and transport
Downtime and waiting	The next stage fails	1	Pull system
	Lack of locksmiths and electricians	1	Organization of work
	Lack of raw materials	1	Conclusion of contracts in accordance with the plan for the supply of raw materials
	Waiting for details	3	Arrangement of equipment in the form of a U-shaped cell
Defects and alteration	Impact, damage during unloading	3	Conduct additional training. Work with suppliers to equip equipment/machines
	Storage damage and chipping	3	Rubber floor, soft plastic and carton packaging

The most urgent and important losses to eliminate at the stage of transportation and storage are the lack of locksmiths and electricians, the lack of raw materials. These problems could have been avoided if quality material had been purchased just in time.

Losses, causes and methods for their elimination at the stage of distribution of materials are shown in Table 3.

Table 3. Losses, causes and methods of their elimination at the stage of distribution of materials

Loss	Cause	Cause Rank	Elimination Methods
Excessive movement	Additional movements for communication	4	Corporate communications, production logistics
	Idling	3	
Overprocessing	Shortage of required materials	3	Availability of safety stock of materials
Downtime and waiting	Out of stock materials	1	Pull production, just in time
	Equipment breakdown	1	Timely purchase of quality spare parts

Particularly important losses at the distribution stage are downtime and waiting due to the lack of materials in the warehouse and equipment breakdowns.

Losses, causes and methods for their elimination at the production stage are presented in Table 4.

Table 4. Losses, causes and methods for their elimination at the production stage

Loss	Cause	Cause Rank	Elimination Methods
Downtime and waiting	Equipment breakdowns	3	Development of projects for the production of works, backup power supply system
	Other breakdowns	1	
	Auxiliary equipment stop	1	
	Lack of electricity	3	
	Lack of materials	3	Organization of work of the department of material and technical supply, introduction of information technologies
	Absence of an employee	2	Organization of work in workshops
	Material delay	3	Organization of work of the material and technical department
	Foreign body entry	2	Self-monitoring system
Excessive movement	Unnecessary movements	3	Staff training 5S, SMED, time management, etc.
	Manual assembly	3	Installation of fixtures
Defects and alteration	Tool wear	2	Availability of a spare tool
	Wrong setup	1	Timely purchase of quality spare parts. Staff training 5S, SMED, etc.
	Hardware failure	2	
	Poor quality materials	2	Organization of work of the department of material and technical supply, work with suppliers
	Human factor	1	Staff training, creation of comfortable conditions, creation of a self-control system
Overprocessing	Alteration due to the fault of workers	3	Creation of an effective system of self-control
	Rework due to equipment failure	3	Modernization of machines
Excess inventory	Feed is not mechanized	3	Modernization of machines
	Workers fail at the next stage	2	Training

Based on the above, we can conclude that it is necessary to monitor the equipment and repair it in a timely manner or, if possible, replace it with a newer and more advanced one, but this no longer applies to lean production.

In addition to losses, the reasons for their formation and methods for their elimination, the lean production model should contain a regulatory framework, principles and tasks (Figure 2).

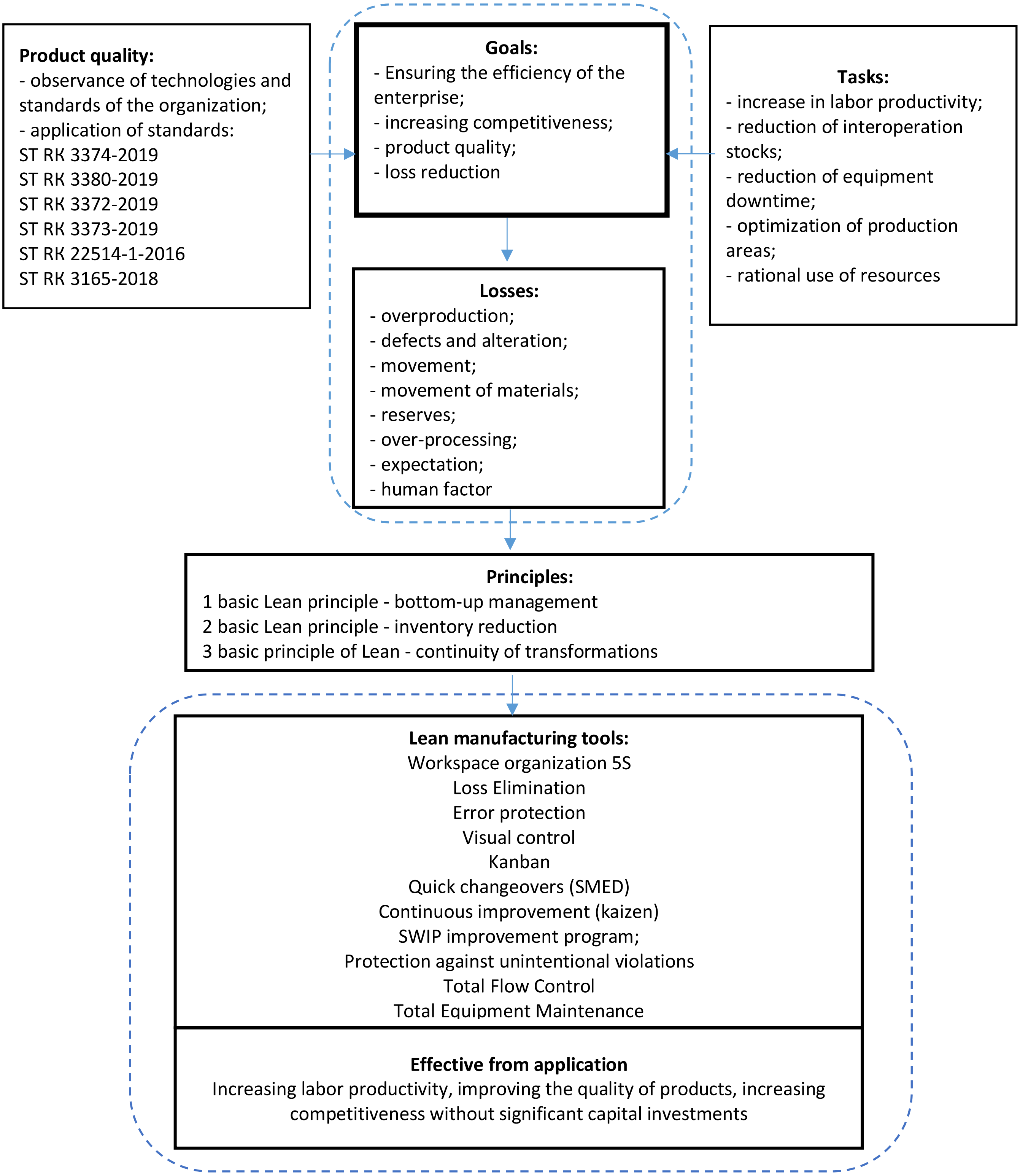

Fig.2. - Model of lean manufacturing at a machine-building enterprise

The principle of bottom-up management implies that employees take the initiative, some of the ideas resonate with colleagues and are supported by the leaders of the organization. Bottom-up is more in demand in predictable conditions, when there is a specific achievable goal.

The principle of "Inventory reduction" assumes that the most profitable all the necessary resources for the production of engineering products can be predicted and not filled with unnecessary warehouses.

The principle of "Continuity of transformations" ensures the improvement of product quality, production potential, staff knowledge and corporate culture.

Thus, the model of lean production of mechanical engineering enterprises will ensure:

- competitive advantages of manufactured products;
- saving resources;
- elimination of unproductive expenses associated with the production of low-quality, technically imperfect and uncompetitive products,
- optimization of the structure of the resource consumption process based on the introduction of new design, engineering and technological solutions that make it possible to increase the completeness of the use of resources,
- the use of economical and non-traditional types of materials and energy sources,
- protection of nature and compliance with environmental requirements;
- reduction of losses of material resources at all stages of production, during transportation and storage;
- reduction of stocks, release of resources at various stages for use in subsequent production cycles.

Summing up all the above, the introduction of a lean manufacturing model at machine-building enterprises improves quality management, reduces costs and downtime, increases the competitiveness of domestic products and increases labor productivity.

Conclusion

1) The model of lean production proposed in the study is necessary to assess the actual state of production at the enterprise and allows you to determine the further direction of development of the production system, and helps to eliminate losses.

2) The tripartite graph provides an interconnection between the types of losses, their causes and methods of elimination.

3) Losses, causes of formation, methods for their elimination can be ranked in order of significance.

4) The principles of lean manufacturing allow you to reduce the cost of all resources used in production without compromising product quality.

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