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Formation of the Integral Ecological Quality Index of the Technological Processes in Machine Building Based on their Energy Efficiency

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ABSTRACT

The aim of article is to provide development of a unified assessment methodology in relation to various technological processes and the actual conditions of their implementation. To carry the energy efficiency analysis of the technological processes through comparison of the established power and the power consumed by the actual technological process during its implementation using real technological equipment, i.e. upon determining the integral ecological quality index of the machine-building technological fabrication processes. This allows to determine the impact of technological processes on the environment due to the energy losses and to implement this process under excessive currents. In this case, the integral ecological quality index is determined by the ratio of the fabrication power set by the technologist and the power consumed by the actual technological process during its implementation using the real technological equipment. The integral ecological quality index is specific due to the fact that it is formed not on with regard to statistical data; it is based on the energy characteristics of the implemented technological process with regard to the real state of equipment and related factors, which are important for assessing the ecological performance of the real technological process.

KEYWORDS
Technological process, power analysis, ecology, energy efficiency, integrated ecological index

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Introduction

Development and implementation of the technological processes in general and technological fabrication processes in machine building in particular is one of the main types of economic activity, which largely defines the economic potential of the country (Yevstratov, 2012).

The implementation of the machine building technological processes related to fabrication is accompanied by the negative impact on man and the environment. This impact is realized through the consumption and wastes, and characterizes the ecological quality indexes of these processes, which in the end significantly define the production competitiveness. Consumption includes first of all the energy required for the implementation of the technological process, as well as transfer of territories with a view to deploy the equipment and additional facilities. Besides, consumption includes the preliminary and auxiliary production required to produce the sub-products and additional

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materials (oils, coolant-cutting fluids, etc.). The wastes include various energy wastes, such as electromagnetic ones, vibration and noise, thermal waste, as well as liquid, solid and gaseous wastes that pollute the atmosphere, hydrosphere and lithosphere (Ivanova & Ryabov, 2015). A large number of the technological processes related to fabrication use the liquid coolant-cutting substances, which produce gaseous wastes upon their decomposition (Ivanova, Ryabov & Shvartsburg, 2014a). As regards the impact of the machine building technological processes related to fabrication on the environment, the wastes also include the products of the machine building industries (time-deferred wastes).

Over the last decades the manufacturing efficiency is more and more determined by its "sustainability", and the energy efficiency is the most important aspect of it. And the integrated approach to the manufacturing process improvements can multiply the benefits (Salonitis & Ball, 2013)

Literature Review

The analysis of the patents related to the energy efficiency in manufacturing showed that there are two categories of patents:

Methods for the recovery of energy for the machining systems

For example system for "Recovery of Energy from a Laser Machining System" that allows recovering heat losses of a laser cooler system using a Sterling engine that drives a compressed air generator. A filter system separates nitrogen and/or oxygen from the compressed air that can be used as assist gas within the machine tool itself (Wahl, Vincke & Himmelsbach, 2011). Dr. A.J. Fisher (2002) developed the method to recover the energy from the compressed air from the industrial fluid compressor. Excess compressed air is bypassed to an energy recovery system that converts the potential energy of the compressed air into electrical or mechanical energy. Generated electrical power may be returned to the main power grid or used to power auxiliary equipment, such as the compressor's oil pump.

Methods of monitoring the manufacturing process

The Energy Department's National Renewable Energy Laboratory (NREL) was recently issued a patent for a novel method that rapidly characterizes specialized materials during the manufacturing process. Characterization of materials using this method is accomplished via wide-angular illumination on the conveyor belt or roll-to-roll processing platform. Spectral imaging and reciprocal optics are then utilized to assess a number of material features including thickness, surface conditions, and uniformity. The industrial control system developed by P.J. Kaufman, E.W. Marcia & S.A. Lombardi et al. (2009) is able to monitor the discrete energy or sustainability factor data and associating such data with a manufacturing component or model. The obtained manufacturing model enhances the efficiencies of the process. There is no patent that presents the comprehensive, integral approach to the energy efficiency of manufacturing process. The energy efficient and sustainable methods are applicable in building (Fluga, 2013), user equipment (Taber, 2001) and even the cookware (Huang, 2014), but not in the manufacturing process. The patents dealing with the environmental impact of the industrial process are focused mostly on the treatment of the existing pollution, not the prevention through development of the energy efficient manufacturing process (Drogui, Blais & Mercier, 2007).

In order to evaluate the impact of the machine-building technological fabrication processes on the environment, it seems expedient to use complex ecological quality index of these processes that could reflect the variety of this impact and provide its quantitative assessment.

However, using the existing methods for objective complex evaluation of the impact of the present machine-building technological fabrication process on man and the environment causes significant difficulties. It is explained by the fact that their evaluation has statistical character. For instance, the ecological risk is quantitatively defined by the possibility of the negative event, its impact on the environment and occurrence of the negative consequences for the environment due to this impact (Ivanova, Ryabov & Shvartsburg, 2014b; Ginko, 2013; Gordeeva & Astafieva, 2014).

Such evaluation methods of the complex impact on man and the environment are difficult to apply for the evaluation of this impact during the implementation of a concrete technological process implemented on concrete equipment having certain wear factor and given certain circumstances – cutting features of a tool, oils and coolant-cutting fluids features, etc.

The suggested methodology is free from this setback. It provides not only numeric assessment of ecological performance of the implemented technological process, but also to evaluate it according to the technical state of the equipment used to implement this process is, the actual state of the cutting tool, oils and coolants, and other related factors.

The scientific value of the suggested methodology is the assumption that the negative impact of machine-building technological fabrication processes on man and the environment is caused by energy losses in the implementation of these processes, and the ecological performance could be numerically assessed by comparing the electric power consumed during implementation of specific processes with the fabrication power calculated by production engineers.

This is very important for the assessment of ecological performance of machine-building technological fabrication processes as it provides the possibility to assess each specific fabrication in terms of its compliance with the quality system requirements, as well as for the timely implementation of measures with a view to reduce the impact of these processes on man and the environment.

As was stated by J.R. Duflou et al. (2012) in comprehensive review of energy efficiency in manufacturing systems the integrated effort for impact reduction and economy improvement can result in at least 50% of global energy consumption reduction in manufacturing.

It should be borne in mind that improving the integral ecological quality index, other quality indexes (metrological, economic, etc.) should not change in the values that exceed the maximum permissible limits.

The suggested approach to the ecological performance assessment of machine-building technological fabrication processes should be used in the machine-building enterprises during evaluation of their compliance with the system quality requirements, in justifying the need for modernization of equipment, tools, as well as for additional measures with a view to clean oils and coolants, as well as to compare the ecological performance of different technological processes.

The objective of this paper is to develop and justify common methodology of a comprehensive assessment of the impact of machine-building technological fabrication processes on man and the environment and numerical evaluation of this impact. This will provide the possibility to improve the ecological performance of technological processes, to justify the timely upgrades (with regard to the ecological performance indices) of equipment and tools, which will ultimately improve the competitiveness of technological processes in particular, and the enterprise in general.

The energy efficiency is one of the key parameters of the manufacturing process. In order to simplify the analysis of the energy efficiency the integral ecological index was developed. The proposed index is comprehensive, providing not only the quantitative statistical analysis, but the evaluation of qualitative parameters, that are specific for each manufacturing process.

In order to carry out complex evaluation of the impact of machine building technological fabrication processes on man and the environment, the authors suggest using the new unified methodology for the whole variety of these technological processes to carry out complex evaluation of this impact (Gvozdkova, 2015). The united methodology provides the possibility to carry out the complex evaluation of the impact of the machine building technological fabrication processes using the integral ecological quality index for the whole variety of technological processes according both to their types and kinds (rotary machining, grinding, milling, etc.), and with regard to their modes (cutting speed, feed rate, cutting depth, etc.), and related factors (oils and coolant-cutting fluids features, etc.) (Golubkov & Ermolaeva, 2012; Shvartsburg et al., 2014).

Aim of the Study

The aim of article is to provide development of a unified assessment methodology in relation to various technological processes and the actual conditions of their implementation.

Research questions

To carry the energy efficiency analysis of the technological processes through comparison of the established power and the power consumed by the actual technological process during its implementation using real technological equipment, i.e. upon determining the integral ecological quality index of the machine-building technological fabrication processes.

Method

The suggested methodology is based on the energy analysis of the technological fabrication processes. The essence of the energy analysis is as follows.

Any machine building technological fabrication process is a reflection of two processes – the process of converting (mainly) electrical energy into the mechanical one and the process of energy transfer to the working area (Figure 1).

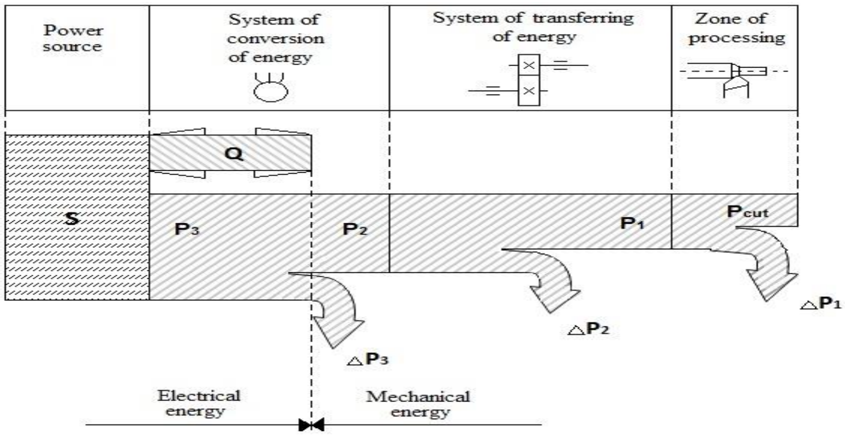

Figure 1. Essence of the energy analysis

The process of converting the electrical energy into the mechanical one is conducted through the electro technical systems of the machine (electrical engines of the main and auxiliary movement, electromagnetic relays, etc.), while the mechanical energy transfer to the working area is conducted through the kinematic chain of the machine (gearbox, the screw-nut pair, etc.).

During the elaboration of the technological fabrication process, the technologist determines the cutting power (P_{cut}) for each technological transition according to the characteristics of the sub-products and tools, the determined cutting modes and availability of the necessary technological transitions. However, in order to transmit the energy determined by P_{cut} to the cutting area, it is necessary provide the working area with a large quantity of energy determined by the P_1 power due to the energy losses in the working area, determined by the ΔP_1 power.

Additionally the energy losses determined by the ΔP_2 and ΔP_3 powers occur both during the mechanical energy transfer to the working area and during the conversion of the electrical energy into the mechanical one. This leads to the fact that giving necessary power to the cutting area requires providing the working area with the P_1 power set to the energy transmission system of the P_2 power, while the energy conversion system should be provided with the P_3 power. Due to the energy losses during all stages of its conversion and transmission to the working area and instant losses in the working area, the implementation of the technological process implies greater power consumption (P_3), than it is necessary for the implementation of the cutting process (P_{cut}).

Considering energy losses in detail, one should keep in mind the following.

These losses determine the impact of the machine building technological fabrication process on man and the environment, which is implemented on the particular equipment and under the particular conditions.

The losses ΔP_1 are determined mainly by the friction in the "tool - detail" system. These losses cause, inter alia, the rise of temperature (thermal waste) in the cutting zone. The application of coolant with a view to reduce the temperature leads to its thermal degradation and therefore – to contamination of the work area.

The losses ΔP_2 are the friction losses and therefore the losses caused by thermal waste, as well as losses associated with the wear of movable elements in the kinematic chain of equipment, i.e. oil pollution with wear products - slurries and impurities.

For example, while transmitting the mechanical energy to the processing area, the presence of gaps in the movable parts of the energy transmission system and stock fluttering in the sub-product leads to losses creating the vibration pollution of the environment resulting in noise pollution.

The losses ΔP_3 are associated with the operation of electrical equipment systems (engines, clutches, relays, etc.). Energy losses occur during conversion of electrical energy into the mechanical one in these systems; this is caused by the presence of electromagnetic fields.

Thus, the energy losses during its conversion and transmission characterize the impact of the machine building technological fabrication processes on man and the environment, and high-energy consumption during the implementation of these processes due to these losses is one of the most important components during the establishment of the integral ecological quality index of the technological processes (Parik & Otto, 2012).

In this regard, one should consider that this ecological index reflects only the implementation of the technological process and does not consider the qualification of the engineer-technologist in the field of the energy and resource-saving technologies determining the minimization of the cutting power ($P_{cut\,\min}$).

Regarding the establishment of the integral ecological quality index of the machine building technological fabrication processes with regard to the energy analysis it is necessary to add the following.

In many cases, these technological processes are implemented on the equipment with the electro technical systems of alternating current. For instance, most of the versatile metal-cutting machines use the three-phase asynchronous engines as the major systems of converting the electrical energy into the mechanical one. The distinctive feature of these engines is the presence of the low power coefficient ($\cos\varphi$) in relation to the shaft power, significantly lower than the nominal power of this engine (underrun of the engine).

The engine's underrun is a typical phenomenon during the implementation of the machine building technological fabrication processes. This is explained by the necessity to conduct technological transitions with different cutting power during one set-up of blank part (finishing and rough turning, drilling, etc.) and the presence of mandatory idle strokes.

The underrun of the asynchronous engine of the metal-cutting machines, resulting in low power coefficient, leads to the further power (S) increase consumed during the implementation of the technological process due to the occurrence of the reactive component of the power consumed (Q). Physically this means that the implementation of the machine building technological fabrication process is carried out under high currents necessary for the implementation of this technological process.

The complete power consumption during the implementation of the machine building technological fabrication processes (S) is determined by the formula:

$$S = \frac{P_{cut} + \sum_{i=1}^{3} \Delta P_i}{cos\varphi}$$

(For the technological processes implemented on the equipment with the electro technical systems of the direct current, the power coefficient is equal to one).

It should be noted that the fact of the energy consumption reduction itself during the implementation of the machine building technological fabrication processes (increasing the energy efficiency of these technological processes) has considerable ecological effect, because the energy production has a significant negative impact on the environment.

Taking into account the above-mentioned, the authors suggest defining the integral ecological quality index of the machine building technological fabrication process (I) through the comparison of the cutting power with the complete power consumed during the implementation of these technological processes.

Thus, the integral ecological quality index will be determined by the formula:

$$I = \frac{P_{cut}}{S} = \frac{P_{cut}}{P_{cut} + \sum_{i=1}^{3} \Delta P_i} * Cos\phi$$

Proceeding from the latter formula, in order to increase the integral ecological quality index of the technological processes (minimization of their impact on man and the environment) it is necessary to increase the power coefficient of the electro technical systems of the equipment, which is used to implement the technological process and/or reduce the energy losses during its implementation. The integral ecological quality index changes within the interval from 0 to 1.

Data, Analysis, and Results

All the above-mentioned was proved through experiments. In order to carry out the comparative evaluation of the comprehensive impact of the machine building technological fabrication processes the integral ecological quality index of two technological processes – the turning process and the drilling process, has been experimentally identified.

During experimental studies, we calculated the power necessary for the implementation of each of the technological processes (P_{cut}) and measured the power consumed during the implementation of these processes (S). According to these data, we calculated the integral ecological quality index of these two technological processes. The results of this correlation are presented in Table 1.

Table 1. Correlation results of the two technological processes

Technological process	*Power of the technological process* (P_{cut}), kW	*Consumed power* (S), kVA	*Integral ecological index* (I)
Turning	1,50	6,05	0,25
Drilling	1,35	3,66	0,36

Thus, the comprehensive impact of the technological drilling process on the environment during its actual implementation is 1.44 times lower than the result of the technological turning process.

The integrated ecological quality index also allows determining the methods and means of minimizing the impact of the machine-building technological processes on the environment during their particular implementation. This statement has been also proved through experiments.

During the experimental studies, the increase of the integrated ecological quality index of the machine-building technological fabrication processes was conducted through the increase of the power coefficient, which low index was determined by the machine underrun, during the implementation of the particular technological process.

The increase of the power coefficient was conducted through the widely known method of the phase displacement (the differential method) (Hamed et al., 2013). In this case, as the coils of the asynchronous engine from the electro technical viewpoint reflect the active-inductive load, the compensation tank is switched on in parallel to each coil phase, providing the compensation of the reactive component of the current consumed, thus, reducing its level.

The experimental studies have been conducted during the technological drilling process. The graphic interpretation of the experimental study results is presented by Figure. 2.

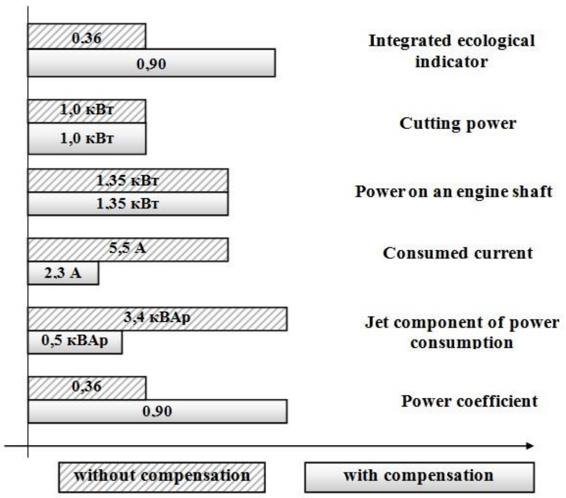

Figure 2. Graphic interpretation of experimental study results

Table 2 presents the data calculated for this process (the cutting power P_{cut}) and the measured indexes before and after the implementation of the differential method (the current consumed - I, reactive component of the power consumed - Q, power coefficient - $\cos\varphi$), as well as the values of the integrated ecological index before and after compensation.

Table 2. The results of the studies related to increasing the integrated ecological index though the compensation method

	Power of the technological process (P_{cut}), kW	*Current consumed* (I), A	*Reactive component of the power consumed* (Q), kVAr	*Power coefficient* ($\cos\varphi$)	*Integrated ecological index* (i)
Without compensation	1,35	5,5	3,4	0,36	0,36
With compensation	1,35	2,3	0,5	0,90	0,90

The results of experimental studies related to the increase in the integral ecological quality index by compensating motor underload showed that the integral environmental quality index increased during the compensation by 2.5 times. The power cut and power on the motor shaft did not change and made 1.0 and 1.35 kW, respectively. Implementation of this process caused significant underload of the engine because its nominal capacity makes 11 kW. The technological process is therefore realized with a low power factor (0.36), high value of the reactive component of power consumption (3.4 kVAr) and high values of consumed currents (5.5 A).

The application of compensation method for increasing the integral ecological quality index promoted further improvement the power factor by 2.5 times, reduce the reactive component of the power consumption to 0.5 kVAr and reduce the amount of current consumed during the implementation process by 2.4 times.

Thus, the compensation method for increasing the integral environmental quality index simultaneously increases the efficiency of these processes, which also has a great ecological value.

The experimental studies therefore showed the efficiency of implementing the method of phase displacement compensation for increasing the integrated ecological quality index of the machine building technological fabrication processes (increase by 2.5 times). It should be noted that the phase displacement compensation not only increases the integrated ecological quality index of the machine building technological fabrication processes, but also reduces the currents consumed during the implementation of these processes, thus, providing the additional safety of the implemented technological process.

Discussion and Conclusion

The conducted theoretical and experimental studies showed the expediency of the complex assessment of the impact of machine building technological fabrication processes on man and the environment through the integrated ecological quality index of these processes (Peng & Xu, 2014). This index should be defined with regard to the ratio between the cutting power set by the production engineer and the power consumed by the technological process during its implementation.

The integrated ecological quality index is determined for each particular implementation of the technological process, it is methodologically unified for technological processes of various types and kinds, takes into account the actual state of the equipment, which is used to implement this process, tool features and other factors contributing to the technological process (Ma et al., 2014).

The importance of this index is also determined by the fact that it allows defining basic ways of its increase (reduction of the impact of the machine building processes on man and the environment), comparing the impact of different technological processes on man and the environment, as well as to defining their specific implementation (Li et al., 2014).

The energy analysis of machine building technological fabrication processes is a universal method of their analysis, as it forms a unified approach to the analysis of various technological processes. This method provides the possibility to represent technological processes by means of two processes - the process of electrical energy conversion into the mechanical energy and the process of mechanical energy transfer to the working zone. This representation takes into account energy losses and the amount of current consumed during the implementation of technological processes.

Methods for the recovery of energy for the machining systems and methods of monitoring the manufacturing process determine the ecological performance of technological processes. Taking into account the fact that cutting power set by the by the production engineer is not related to the actual implementation of the process (the state of the equipment and tools, real properties of oils and coolant and other factors), the ratio of the actual power consumption and the cutting power characterizes the ecological performance of the technological process during its particular implementation. This is determined by the fact that the actual power consumption besides cutting power considers energy losses and the amount of consumed current, i.e. the real conditions of the specific implementation of technological process. Thus, this ratio determines the ecological performance of specific implementation of technological process and can be regarded as the integral ecological index.

Experimental studies on the example of turning and drilling operations showed the possibility to carry out numerical assessment of ecological performance of machine-building technological fabrication processes, which is common for various processes. In addition, they showed the possibility to carry out numerical assessment of measures taken to improve the ecological performance of technological processes, as well as timeliness of these measures.

The significance of the integral ecological quality index is further emphasized by the fact that it is formed by a single method for each particular implementation of different types and kinds of technological processes.

Implications and Recommendations

The article presents the methodology of solving the problem related to complex assessment of the ecological performance of the machine building technological fabrication processes on the environment taking into account the real state of equipment, tools and other supporting factors, which is important to carry out numerical assessment of these processes on man and the environment.

Solution of this problem is based on the energy efficiency analysis of the technological processes through comparison of the established power and the power consumed by the actual technological process during its implementation using real technological equipment, i.e. upon determining the integral ecological quality index of the machine-building technological fabrication processes. This gives the possibility to consider the cumulative impact of these technological processes on man and the environment, which is determined by the energy losses and high indexes of the currents consumed during their particular implementation on the particular equipment. Additionally, it is possible to identify both the cumulative impact of the technological process in general and each technological transition in particular, which provides the possibility to determine the well-founded technical solutions directed at improving the integral ecological quality index of the machine-building technological fabrication processes, forecasting and minimizing the impact of these processes on man and the environment.

Thus, the energy approach to the analysis of the impact of technological fabrication processes, implementation of results aiming at the improvement of energy efficiency of technological processes, the numerical assessment of their impact on man and the environment provides development of a unified assessment methodology in relation to various technological processes and the actual conditions of their implementation. The integral ecological quality index of technological processes determined through the energy analysis gives the possibility to compare these processes with regard to their combined impact on man and the environment.

The factor, which causes the impact of machine-building technological fabrication processes on man and the environment, lies in energy losses during its conversion and transmission to the working zone, and the overrated consumption of currents during their implementation given the cutting power set by the production engineer.

The energy representation of machine-building technological fabrication processes as two processes - the process of electrical energy conversion into the mechanical energy, and transfer of mechanical energy into the working zone provides the possibility to create a uniform numerical assessment of ecological performance for different technological processes based on the integral ecological index, taking into account energy loss and implementation of these processes at excessive currents. The integral ecological index is calculated by comparing the cutting power and the working power.

The integral ecological index gives the possibility to compare the machine-building technological fabrication processes with regard to their ecological performance, to identify ways aimed at its raising and to provide the timely upgrading of equipment used for implementation of these processes.

Presently, the authors are working on the determination of algorithms and schematic solutions on improving the integrated ecological quality index of the machine building technological fabrication processes using the automation assets.

Disclosure statement

No potential conflict of interest was reported by the authors.

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