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USE OF EVOLUTIONARY METHODS FOR THE SIMULATION OF WEAR PHENOMENA IN TECHNOLOGICAL PROCESSES OF SHAPING MATERIALS

Key words: evolution algorithms, prediction, stamping, wear.

Abstract: The article presents an implemented solution, which includes an aspect of work that has been done on modelling for the purposes of simulation processes, carried out under the Multi-Year Programme "Improvement of Innovation Development Systems in Production and Maintenance Processes". The method described in this article relates to the prediction of wear processes of tools, which are used in shaping processes of materials by plastic formation, including cold sheet metal stamping. The research problem presented in this article was determined by the identification of specific characteristics of wear processes on stamping technology, based on which a computational prediction model based on computerized methods of data processing was developed. This method streamlines complex processes of exploitation, including the need to anticipate the time that tools must be replaced. The article discusses identified research and application problems that had to be solved during the design and implementation of the solution. The theoretical basis of exploitation processes, types of technical states, diagnostic methods, as well as the structure of the developed solution and its basic features are shown. Important elements of this paper include the possibilities of using the method for tasks related to ensuring the continuity of production in industrial factories that use sheet metal stamping systems. Innovative features of the developed system are also discussed.

Wykorzystanie metod ewolucyjnych do symulacji zjawisk zużycia w technologicznych procesach kształtowania materiałów

Słowa kluczowe: algorytmy ewolucyjne, prognozowanie, tłoczenie, zużycie.

Streszczenie: W artykule zaprezentowano rozwiązanie obejmujące fragment prac dotyczących modelowania na potrzeby symulacji procesów technologicznych realizowanych w ramach Programu Wieloletniego „Doskonalenie systemów rozwoju innowacyjności w produkcji i eksploatacji". Opisana w artykule metoda dotyczy predykcji procesów zużycia narzędzi wykorzystywanych w procesach kształtowania materiałów poprzez obróbkę plastyczną obejmującą tłoczenie blach na zimno. Problem badawczy podjęty w artykule określony został poprzez zidentyfikowanie specyficznych charakterystyk procesów zużycia dotyczących technologii tłoczenia, na podstawie których opracowano obliczeniowy model prognostyczny oparty na komputerowych metodach przetwarzania danych. Metoda usprawnia złożone procesy eksploatacji, w tym potrzebę przewidywania okresu, po jakim zachodzi konieczność przeprowadzenia regeneracji lub wymiany narzędzi. W artykule omówiono zidentyfikowane problemy badawcze i aplikacyjne, które należało rozwiązać podczas projektowania i implementacji rozwiązania. Przedstawiono podstawy teoretyczne procesów eksploatacji, rodzaje stanów technicznych, metody diagnostyczne, a także strukturę opracowanego rozwiązania i jego podstawowe funkcjonalności. Zaprezentowano możliwości wykorzystania metody do zadań związanych z zapewnieniem ciągłości produkcji w zakładach przemysłowych użytkujących systemy tłoczenia blach. Wskazano na innowacyjne cechy opracowanego systemu.

Introduction

Processes associated with wear of tools are an important issue related to production processes that are carried out in enterprises that operate in the areas of production and service. Machine arrays may be highly diversified, which can further complicate the issue. Not replacing worn tools with new tools at a specified time or the failure to renovate them may result in financial losses. These losses can be magnified if worn tools cause damage to the machine in which they were installed. In addition, the quality of manufactured products is determined partly by the technical condition of the machines that produced them. The use of worn tools increases the risk of accidents at work in many cases. A significant problem is the prediction of the time when the procedures of exchange should begin. In some cases, the examination of tools is not a problem, and can be performed at any time, but in the case of machines that are constructed in a manner that makes the removal of tools within acceptable time limits difficult, due to complicated access to them, performing certain measurements can pose a serious problem. In these cases, the correct prediction of the time when the tool should be replaced or regenerated is a key issue. Due to the considerable diversity of tools and the processes that are carried out with the use of them, this is a multidimensional issue. Some of the problems associated with the wear of tools can be identified indirectly and organoleptically (visual condition, sounds of working machine, vibrations), but there is also the risk of misdiagnosis. The elimination of these problems requires proper diagnosis and then requisite actions to rectify the situation. Progress in the area of data processing has enabled the development of increasingly sophisticated diagnostic techniques that allow for the effective analysis of wear symptoms, as well as prediction of critical changes, and the elimination of human factors, which ensures an increase in the objectivity of results. Based on data analysis, it is possible to carry out simulation processes and, consequently, the generation of conclusions [1]. By changing input factors of analysed systems (e.g., types of workpieces, the number of manufactured products within specified periods of time, etc.), it is possible to determine different variants of tool wear characteristics and the selection of the best options, which can generate real profits for companies. The simulations may take into account numerous factors associated with wear of elements as well as replacement costs. This approach can be applied to both existing production lines and new lines.

1. Characteristics of wear processes

There are many definitions of technical wear, which are connected with its various characteristics. The most general definitions define wear as a permanent, undesirable change of the element state that occur during exploitation continuously or discretely, as a result, the element continuously decreases its function over time [2]. According to another definition, it is a process of the change in the surface layer of a solid, the result of which can be measured by volume or weight [3]. Wear processes can be classified in terms of cause (tribological and non-tribological), development (stable and unstable), and effects (normal and emergency). Due to the cause, there can be distinguished such basic types of tribological wear as mechanical (mainly caused by friction between co-operating surfaces), fatigue (local loss of homogeneity and associated material losses caused by impact of cyclic contact stresses in surface layer of cooperating elements), adhesive (destruction of surface layer of cooperating elements as a result of creation and tearing of adhesive connections and microwelds, which form between the tops of bumps of cooperating surfaces), thermal (changes in material properties caused by the effects of heat), diffusive (penetration of material' structures by the atoms of another material), chemical (caused by the effects of chemical factors), erosive (caused by the impact of abrasion which causes furrows, grinding, microslicing, etc.), hydrogen (caused by penetration of surface structure by hydrogen under specified thermal conditions), and other causes. Different types of wear may affect general wear to varying degrees. An example of the impact of selected types of wear on general wear of cutting tools is shown in Fig. 1. Identification of the type of wear is a complex process due to the large number of variables that influence the course of the wear process. The rate of technical wear is conditioned by many complex factors, including factors involving materials, construction, and exploitation. Among these, an important role is play by chemical and phase composition, microstructure, mechanical properties of materials, the condition and value of stresses, fracture toughness, corrosion resistance, conditions and types of use (continuous or periodic operation), the manner and nature of loads, the type of work environment, etc. Wear status of technical objects is determined by a set of characteristic attributes. There are two basic states of wear: usability (object can carry out established functions), unusability (object cannot carry out established functions). Some publications [4] mention a third state of wear – partial usability (object cannot carry out all established functions). Changes in technical state are associated with processes in technical object or its surroundings, and they can be reversible or irreversible. They can also be classified into one of three basic groups: critical (which cause danger to the life and health of users, as well as the environment), boundary (which can adversely affect the performance of the machine), and acceptable (which may affect originally established methods of use of the object). Processes of wear in a technical object are shown in Fig. 1.

If none of attributes that characterize the technical state of an object exceeds the limit value, then it is recognized that the technical and operational properties of the object are consistent with assumptions regarding design and implementation, and that the object can fully carry out the tasks for which it was designed.

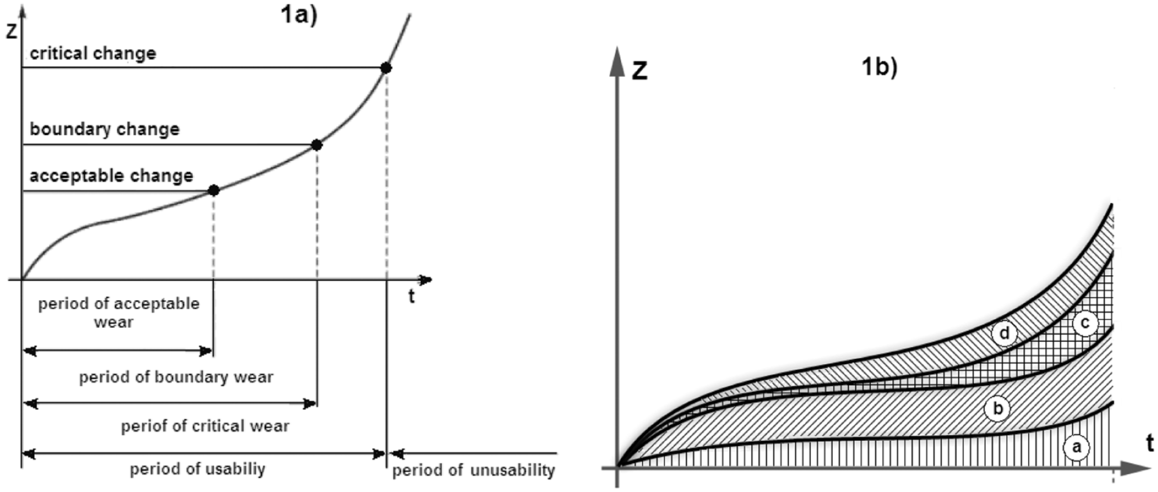

Fig. 1. **Processes of wear in technical objects 1a) and examples of the contribution of different types of wear in general wear during the use of cutting tools 1b): *Z* – degree of wear, *t* – time, *a* – adhesion, *b* – diffusion, *c* – attrition, *d* – plastic deformation**

2. Prediction model of wear in processes of cold sheet stamping

The proposed solution is designed for the prediction of the process of die wear, in order to determine the moment for replacement or regeneration. This allows for the improvement of processes of production planning, and the reduction of downtime and an increase in the quality of products. The general model represents a system, the function of which is to transform input values X_M, into output volumes Y_M with the use the operator F_M. The general notation of a formal model is as follows:

$$F_M : X_M \to Y_M \tag{1}$$

where F_M – operator of the model; X_M – space of input values; Y_M– space of output values.

The space of input values X_M is a set of properties of the dies elements, properties of materials used in stamping process, and requirements for manufactured products as follows:

$$X_M = \{X^T, X^A, X^W\} \tag{2}$$

where

X_M – space of input values;

$X^T = \{x_1^T, x_2^T, ..., x_i^T\}$ – set of properties of dies elements;

$X^A = \{x_1^A, x_2^A, ..., x_j^A\}$ – set of properties of materials used in stamping process;

$X^W = \{x_1^W, x_2^W, ..., x_k^W\}$ – set of requirements for manufactured products.

The space of output values Y_M is a set of information on replacement or regeneration of dies:

$$Y_M = Y^G \tag{3}$$

where

Y_M – space of output values;

$Y^G = \{y_1^G, y_2^G, ..., y_m^G\}$ – set of information on replacement or exchange of dies.

It was assumed that the point of reference for individual measurements of die wear is the state before beginning the stamping processes $i = 0$ (i – number of stamping process cycle) associated with production of specific products. It was assumed that for this state value of wear coefficient Z_0 will be 0. The wear coefficient is defined as an intermediate volume expressed by the equation as follows:

$$Z_i = \max\left(\frac{G_n^i - G_n^0}{G_n^d - G_n^0}\right) * 100\% \tag{4}$$

where

n – number of dimension of product geometry;

i – number of cycle of stamping process;

Z_i – wear of die elements in ith cycle of stamping process;

G_n^i – nth dimension of stamping geometry for ith cycle of stamping process;

G_n^0 – nth dimension of die stamping geometry before beginning of stamping process cycles, $i = 0$;

G_n^d – acceptable limit value of nth geometry dimension (boundary value resulting from geometrical requirements on manufactured product).

The number of geometrical dimensions relates to requirements for parameters of manufactured products.

Geometric measurements of products are necessary because of the need to collect data, based on which, it is possible to subsequently determine the wear curve. It was assumed that the wear curve will be a function, the domain of which is expressed in working cycles of machine press. The assumption has been adopted because pauses may occur in production processes associated with time irregularity in the manufacture of certain products; therefore, a domain expressed in working cycles is more favourable than a domain expressed in units of time. The smallest number of measurements for which a wear curve is determined is 3. In the case of two measurements, it is possible to determine wear that only has a linear nature. It is important that measurements of wear should be carried out in the area of acceptable changes; otherwise, it is not possible to estimate the point at which the tool should be regenerated or replaced before the actual occurrence of critical changes in its structure. After determining coefficient of wear for the *i*th cycle of the stamping process, the curve of wear is calculated (so-called Lorenz curve [5]), the shape of which is mapped using the original mathematical equation (MWF – Modular Wear Function) developed for the model ():

$$f(i) = \left(\alpha * \ln(i * \tau) + \beta * e^{(i^* \gamma)}\right) * \delta + \eta \qquad (5)$$

where

$\alpha, \beta, \gamma, \eta, \tau$ – coefficients forming wear curve;
i – stamping process cycles (independent variable).

In the developed mathematical model, the following three modules can distinguished:

$\alpha * \ln(i * \tau)$ – logarithmic module which maps preliminary wear;
$\beta * e^{(i^* \gamma)}$ – exponential module which maps final wear;
$\delta + \eta$ – module of scaling and translation.

Examples of wear curves determined with the use of the developed model are shown in Fig. 2.

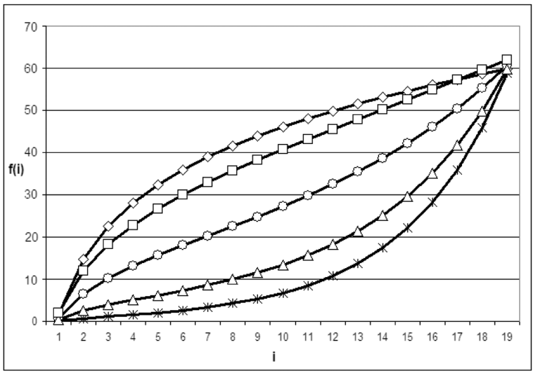

Fig. 2. Example of wear curves determined with the use of the developed mathematical model

Mapping the wear curve is also possible with the use of other mathematical models, such as polynomials [6]. The advantage of the developed model is that the proposed function is monotonic; therefore, it coincides to a much greater extent with the actual representation of wear processes. Further processes of the determination of wear curve coefficients based on data collected during periodic geometry measurements can be carried out. For this purpose, genetic computational models, which are a group of algorithms used to search the space of alternative solutions in order to identify what is optimal for a particular problem task, were used. The method of the operation of genetic algorithms, which are a subset of evolutionary models [7], is similar to phenomena that occur in biological processes based on the phenomena of natural selection and heredity. Calculations are based on the principle that the best adapted units (close to optimum) that carry information (chromosomes) on how to resolve a specific problem are subject to replication processes in order to maximize information contained therein, and these chromosomes mutually crossbreed and mutate to increase their diversity. The analysed problem maps the environment in which a specific group of individuals operates that carries information (a "population"). Characteristic features of genetic algorithms are a parallel search space of solutions and the use of stochastic elements [8]. Genotypes of the population of individuals have been encoded in chromosomes. Binary representation of a genotype is a vector $v = (v_1, .., v_n)$, which is a concatenation of binary strings that represent individual coefficients of wear curve, as well as auxiliary variables that are associated with data processing by genetic algorithm. Individual coefficients that shape wear curves have been encoded in a binary manner in genotypes of chromosomes with an accuracy of 6 decimal places, which the use of 27 bits. Encoding has been implemented using the Gray code [9], so that transition between two adjacent values is carried out by changing the state of a single bit. Based on analysis of literature [10] and empirical studies, parameters of the process of the evolution have been matched, as shown below:

- The population of individuals with genotype encoded: 200;
- Mutation probability for a single individual in a single epoch: 0.04;
- Crossbreeding probability for a single individual in a single epoch: 0.8; and,
- The number of epochs (generations of individuals): 3000.

The adaptation function of individuals to the environment is defined as the sum of distances between values of the wear coefficient for selected cycles of the stamping process and the empirical values of wear for analogous cycles. The developed equation of the fitness function is shown below.

$$P=\sum_{i=1}^{n}\sqrt{\left(\left[\left(\alpha*\ln(i*\tau)+\beta*e^{(i*\gamma)}\right)*\delta+\eta\right]-z_i\right)^2} \quad (6)$$

where
P – adaptation of wear function to empirical data;
$\alpha,\beta,\gamma,\eta,\tau$ – coefficients that form the wear curve;
i – cycle number of stamping process,
n – measurements number of wear;
Z_i – wear coefficient for *i*th cycle of the stamping process.

The process of evolution is repeated iteratively until boundary conditions, such as the maximum number of iterations, the maximum duration of the process of determination of coefficients that form the wear curve and accuracy of the curve that fit empirical data on wear, are met. After the determination of parameters of the wear curve, it is possible to estimate the end of the period of acceptable wear after which elements of the die should be regenerated or replaced. It was assumed that, for the period of acceptable wear, the value of the wear coefficient is 100%. When a set of parameters of wear characteristics has been established, it is possible to estimate the stamping cycle based on empirical data, after which the wear coefficient reaches 100%. Determination of the wear cycle *i* from equation (1) is possible with the use of numerous numerical methods [11]. The proposed solution uses a method based on bisection [12], where, instead of classical search for Zero of a function, the search is for a place where function wear reaches 100%. Because the wear function during the sample interval is a monotone function, the method thereby satisfies assumptions on the possibility of estimation of the stamping cycle for which the function takes the value 100%.

3. Verification

The correctness of the model assumptions that concern the possibility to estimate wear of stamping parts was verified by empirical research. During the first stage of verification work research subjects were selected, which were elements of covers of electric motors (labelled as A) and propeller of industrial fan (labelled as B) (Fig. 3). The elements were manufactured with the use of cold stamping technology. For both elements, the accuracy of assumed shapes is 0.5 mm.

Due to long term of process associated with wear of stamping dies, for verification purposes (shortened time of verification), it was assumed that the required accuracy of manufactured parts is 0.1 mm. According to adopted methodology, it was assumed that that the wear of the die was 0% before the stamping process. Subsequently, a check of the dimensions of every 1000th manufactured item was conducted. Results that include values of wear coefficients and estimated stamping cycles, after which the value of the wear coefficients reach 100%, are shown in Table 1.

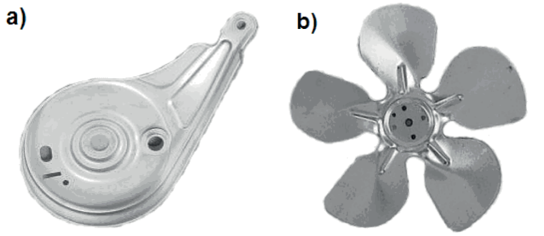

Fig. 3. Elements used for verification of the model, manufactured with the use of cold stamping technology: a) cover of electric motors, b) propeller of industrial fans

Table 1. Wear coefficients and estimated stamping cycles that end periods of acceptable wear for stamping processes of elements used in the verification of the model

Stamping cycle	Wear coefficient		Estimated stamping cycle that ends period of acceptable wear	
	A	B	A	B
1000	1.2	1.4	–	–
2000	7.5	5.2	–	–
3000	9.1	8.8	13420	18534
4000	10.7	9.7	17013	15121
5000	11.6	10.6	16147	14542
6000	20.4	11.2	1373	12234
7000	35.9	13.5	746	8234
8000	64.2	16.2	462	5866
9000	100	27.2	124	2463
10000	-	46.7		834
11000	-	70.4		424
12000	-	100		72

The difference between expected cycles that end periods of acceptable wear i_p, and analogous actual cycles i_r, as a function of number of geometric measurements of manufactured products taken into account during the estimation of wear function is shown in Fig. 4.

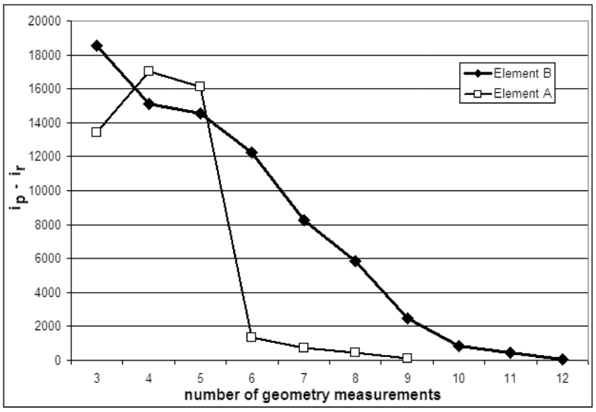

Fig. 4. The difference between expected cycles that end periods of acceptable wear and analogous actual cycles as a function of numbers of geometry measurement of manufactured products taken into account during estimating of wear function

Based on these results, it was found that it is possible to estimate the cycle that end periods of acceptable wear, and these can change depending on the number of measurements, on the basis of which the wear curve is determined. The tendency associated with the accuracy of obtained results shows that the greater the number of measurements of wear, the more accurate is the final result. The obtained results indicate the correctness of the model assumptions.

Conclusions

The solution that has been described in this article is designed to predict the wear of machines elements in production processes of shaping materials by treatment in the form of metal stamping with the use of computational methods have been implemented and are used in practice. The uses of tools are affected to a certain extent by attempts to improve the efficiency of the planning of operational processes (in particular those associated with elements of dies) and the reduction of costs associated with unplanned downtime of production lines. This has an impact on the reduction of financial losses related to the lack of continuity of production. The larger the scale of production, the greater is the potential benefits of the use of the developed solution, which can have a significant positive financial impact on a company. A significant advantage of this method is also its universality, which lies in possibility of being used for a wide range of manufactured products in processes of stamping and a wide range of stamping machines. A significant impact on the obtained results is the number of measurements related to the geometry of manufactured items. More measurements usually makes it possible to obtain more accurate results related to prediction of cycle, after which elements of die must be regenerated or replaced. Advantages of the method become more pronounced the more complex the structures are of manufactured items. Planning of wear processes with the use of the developed method reduces downtime and the involvement of the technical staff in the restoration of machines involved in production. The developed solution, beyond its purely technical aspects, can also be a teaching aid in the training of technical personnel (acquiring competencies related to the operation of stamping machines), which could give a broader and more comprehensive application potential of the tool.

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