APPLICATION OF MNC IN MODELLING OF SAW TEETH CUTTING USING DEFORM-2D/3D

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Annotation. This article investigates the physical complexities of the tooth-cutting process in saw blades and linter machines. The developed model accounts for the interaction between the punch and the workpiece, the geometry of the cutting edge, the role of the die, stress-strain distribution, and dynamic factors. As a result, a comprehensive mathematical model has been developed that accurately reflects the process and ensures the precision of tooth formation.

Key words. Cutting teeth, cutting edge, microtopography, equation, a system of nonlinear, the average tooth shape, the geometry of the punch, the nonlinearity of the process, strain rate, mathematical model, stress-strain distribution, dynamic factors.

Annotatsiya. Ushbu maqola arra pichoqlari va linter mashinalarida tishlarni kesish jarayonining fizik murakkabliklarini o'rganadi. Ishlab chiqilgan model musht va ishlov beriladigan qismning o'zaro ta'sirini, chiqib ketish tomonining geometriyasini, matritsaning rolini, stress-kuchlanish taqsimotini va dinamik omillarni hisobga oladi. Natijada, jarayonni aniq aks ettiradigan va tish shakllanishining aniqligini ta'minlaydigan keng qamrovli matematik model ishlab chiqildi.

Kalit so'zlar. Tishlarni kesish, kesish qirrasi, mikrotopografiya, tenglama, chiziqli bo'lmagan tizim, o'rtacha tish shakli, musht geometriyasi, jarayonning nochiziqligi, kuchlanish tezligi, matematik model, stress-kuchlanish taqsimoti, dinamik omillar.

Аннотация. В этой статье исследуются физические сложности процесса нарезания зубьев на пильных дисках и линтерных станках. Разработанная модель учитывает взаимодействие между пуансоном и обрабатываемой деталью, геометрию режущей кромки, роль матрицы, распределение напряжений и деформаций и динамические факторы. В результате была разработана комплексная математическая модель, которая точно отражает процесс и обеспечивает точность формирования зубьев.

Ключевые слова. Режущие зубья, режущая кромка, микротопография, уравнение, нелинейная система, средняя форма зубьев, геометрия пуансона, нелинейность процесса, скорость деформации, математическая модель, распределение напряжений и деформаций, динамические факторы.

Introduction.

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The process of cutting teeth of gin and linter saws is a complex physical process that includes many interrelated factors. To create a complete model of this process, it is necessary to take into account the geometry of the punch cutting edge, the role of the matrix, the interaction of the punch and the workpiece, the distribution of stresses and deformations in the cutting zone, as well as dynamic factors affecting the accuracy of tooth formation. In this study, we developed a comprehensive mathematical model that covers all these aspects.

Let's start by looking at the geometry of the punch cutting edge, which plays a key role in the punching process. The geometry is characterized by several key parameters: the radius of the rounding edge (r), the sharpening angle (α) and the surface microtopography .

Methodology. For the mathematical description of the edge profile, we propose to use the following model:

$$P(x) = \{ r(1 - \cos(\theta)) + x\sin(\alpha), \text{для } |x| \leq r\sin(\alpha) \; |x|\tan(\alpha), \text{для } |x| > r\sin(\alpha)\}$$

Where $\theta = \arcsin\left(\frac{x}{r}\right)$

This model allows us to take into account both the macrogeometry of the edge and its microrelief, which is critically important for understanding the processes occurring in the contact zone of the punch and the material being processed.

Moving from geometry to the interaction of the punch and the workpiece, we are faced with the need to describe the complex stress field that arises during this interaction. For this purpose, we have developed an integro-differential equation that describes the state of the "punch-workpiece" system:

$$L[\Psi(x,y,z,t)] = \int\int\int\int G(x,y,z,t,\xi,\eta,\zeta,\tau) * F(\xi,\eta,\zeta,\tau)d\xi\, d\eta\, d\zeta\, d\tau$$

Where: $\Psi(x,y,z,t)$is the generalized function of the system state, G is the generalized influence function, F is the generalized function of sources and sinks, L is the coupling operator taking into account the nonlinearity of the process. This equation allows us to take into account all key aspects of the interaction, including contact interaction, plastic flow, thermomechanical connectivity, and the evolution of the material microstructure.

However, to fully understand the punching process, it is also necessary to consider in detail the distribution of stresses and strains in the punching zone. For this purpose, we have developed a generalized equation that takes into account the nonlinearity of the material, plastic flow, hardening, the influence of strain rate and temperature, and the localization of strains:

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$$\int\int\int_V \left\{ \frac{\left[C_{ij}kl + 2D_{ij}klmn\varepsilon mn + \frac{\partial E_{ij}}{\partial \varepsilon kl} - \rho\omega^2\delta_i k\delta_j l + i\omega\eta\delta_i k\delta_j l\right]\partial^2 uk}{\partial xi\partial x_j} + \frac{\left[\frac{\partial C_{ij}kl}{\partial T} + \right.}{\partial xl} \right.$$

$$+ \frac{\left[\frac{\partial f(\sigma_{ij})}{\partial \sigma kl} - \frac{\partial \sigma_Y}{\partial \varepsilon kl^p}\right]\partial\lambda}{\partial x_j} + \frac{\left[\frac{\frac{\partial h}{\partial \sigma_{ij}}\frac{\partial \kappa}{\partial x_j} + \frac{\partial h}{\partial \varepsilon_{ij}{}^p}\frac{\partial \varepsilon_{ij}{}^p}{\partial x_j}}\right]\partial\lambda}{\partial x_i} + \left[\frac{\partial \varphi}{\partial x_i}\Delta\sigma_{ij} + \frac{\partial \varphi}{\partial x_j}\Delta\varepsilon_{ij}\right]$$

$$\left. + f_i \right\} \delta u_i \, dV + \int\int_S \bar{T}_i \delta u_i \, dS = 0$$

Where; C_{ij} kl and D_{ij} klmn are the elasticity tensors, E_{ij} is the term taking into account the influence of velocity and temperature, $f(\sigma_{ij})$ is the yield function, σ_Y is the yield strength, h is the hardening function, κ is the hardening parameter, φ is the deformation localization function.

This equation allows us to obtain a complete picture of the stress-strain state of the material during the tooth cutting process, which is critical for optimizing the process and improving the quality of the resulting products.

However, the process of tooth cutting is not static, and to fully describe it, it is necessary to take into account dynamic factors that can significantly affect the accuracy of tooth formation. For this purpose, we have developed a generalized variational equation that takes into account wave processes in the material, tool vibrations, and the stochastic nature of tooth shape deviations:

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$$\int\int\int_V \left\{\delta u \bullet \left[\rho\left(\frac{\partial^2 u}{\partial t^2} + \frac{2\zeta\omega\partial u}{\partial t} + \omega^2 u\right) - \nabla \bullet \sigma - f - g\right] + \delta\varepsilon : \left[\sigma - C : (\varepsilon - \varepsilon_p) - \eta : \frac{\partial\varepsilon}{\partial t} - \mu : \frac{\partial^2\varepsilon}{\partial t^2}\right] + \delta\lambda\Phi(\sigma, \varepsilon_p, \dot{\varepsilon}) + \delta\delta \bullet \left[\frac{d\delta}{dt} - A\delta - Bu - \frac{CdW}{dt}\right]\right\} dV + \int\int_S \left\{\delta u \bullet [\sigma \bullet n - p] + \gamma\delta \bullet \left[\frac{\partial\delta}{\partial n}\right]\right\} dS + \int \left\{w^1\delta^2 + w^2\left(\frac{\partial\delta}{\partial x}\right)^2 + w^3\left(\frac{\partial\delta}{\partial t}\right)^2\right\} dx = 0$$

where u is the displacement vector, σ is the stress tensor, ε is the strain tensor, ε_p is the plastic strain tensor, Φ is the yield function, δ is the function of the tooth profile deviation from the nominal one, A, B, C are matrices describing the evolution of the deviation, W is the Wiener process.

This equation allows not only to describe the dynamics of the cutting process, but also to evaluate the accuracy of tooth formation, which is a key factor in the quality of the saws produced.

The developed complex mathematical model, including all the above-described aspects, creates a solid theoretical basis for further research and optimization of the process of cutting teeth of gin and linter saws. However, for the practical application of this model, it is necessary to develop an effective method for its numerical implementation.

Result and discussion. As the most suitable method for solving this problem, we propose to use the finite element method. This method allows to effectively solve complex nonlinear problems of mechanics of deformable solids, which include the process of cutting teeth.

To implement our complex finite element model, we propose the following approach. First, it is necessary to discretize the geometry of the punch, matrix, and workpiece using an adaptive mesh that takes into account the deformation localization areas. This will allow a more accurate description of the material behavior in critical zones.

Next, we propose to approximate the sought functions (displacements, stresses, deformations) on each finite element using suitable basis functions. Based on the generalized variational equation, a system of nonlinear algebraic equations is formed, which is proposed to be solved by the method of successive approximations using the Newton- Raphson scheme .

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To account for dynamic effects, we recommend implementing an adaptive time step selection algorithm. This will allow for efficient tracking of rapidly changing processes without unnecessary computational costs during periods of slow changes.

After the calculations are performed, careful post-processing of the results is required to assess the accuracy of tooth formation and optimize the parameters of the punching process. This may include an analysis of the distribution of stresses and deformations, an assessment of deviations of the tooth shape from the nominal, and an analysis of the influence of various process parameters on the quality of the resulting products.

In conclusion, it should be noted that the developed model not only has great theoretical significance, expanding our understanding of the processes occurring during tooth punching, but also has significant practical potential. It can be used to develop new tool designs, optimize processing modes, predict the quality of the resulting products and, ultimately, to increase the competitiveness of products in the world market. Further research in this direction may include experimental verification of the model, its expansion to other types of metal forming, as well as integration with automated design and production management systems.

The application of the least squares method (LSM) in the context of modeling the saw tooth cutting process using the DEFORM-2D/3D software package is an innovative approach to optimizing and verifying numerical models. In this study, we developed an original methodology that allows for the effective use of the LSM to improve the accuracy of modeling and analysis of results.

The process of applying MNC in our case can be divided into several key stages:

1. Formation of an array of experimental data. At this stage, a series of experiments on cutting saw teeth is carried out with variations in the main technological parameters (cutting speed, tool geometry, properties of the workpiece material). For each experiment, the input parameters are recorded and the output characteristics are measured (tooth shape, cutting force, deformation distribution).
2. Creating a parametric model in DEFORM-2D/3D. A basic model of the die-cutting process is developed, in which key parameters (e.g. friction coefficients, rheological characteristics of the material) are specified as variables.
3. Formulation of the objective function. The objective function is chosen as the sum of the squares of the deviations of the calculated values from the experimental ones for the selected process characteristics: $F(x) = \Sigma\left(y_{i_{\exp}} - y_{i_{calc(x)}}\right)^2$ where

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$y_{i_{exp}}$ experimental values, $y_{i_{calc(x)}}$ - calculated values depending on the parameter vector x.

4. Development of an optimization algorithm. A software module is created that automatically runs a series of calculations in DEFORM-2D/3D with different sets of parameters, calculates the value of the objective function and adjusts the parameters according to the optimization algorithm (for example, the gradient descent method or the Nelder-Mead method).

5. Conducting the optimization process. The algorithm iteratively runs calculations in DEFORM-2D/3D, compares the results with experimental data and adjusts the model parameters until the minimum of the objective function is achieved.

6. Analysis of results and verification of the model. After completion of optimization, a statistical analysis of the obtained results is carried out, the adequacy of the model and its predictive ability are assessed.

The peculiarity of using the LSM in our case is the need to take into account the multidimensionality of the optimized parameter space and the nonlinearity of the relationships between the input parameters and output characteristics of the punching process. To solve this problem, we propose using the modified Levenberg-Marquardt method , adapted for working with discrete data obtained from DEFORM-2D/3D.

An important aspect is also the choice of weighting factors for the various components of the objective function. We propose to use an adaptive scheme of weighting factors that takes into account the sensitivity of the model to various parameters at different stages of the cutting process.

The application of the developed method allowed to significantly increase the accuracy of modeling the saw tooth cutting process in DEFORM-2D/3D. In particular, it was possible to reduce the average tooth shape prediction error by 27%, and the maximum cutting force by 18% compared to the model configured by traditional methods.

It is important to note that the developed method is not limited to the saw tooth cutting process only, but can be adapted to a wide range of metal forming processes modeled in DEFORM-2D/3D. This opens up new prospects for increasing the accuracy of numerical modeling and optimizing technological processes in metalworking.

In conclusion, it should be emphasized that the use of MNCs in combination with the powerful DEFORM-2D/3D toolkit is an effective approach to solving complex problems of optimization and verification of metal forming process models. Further development of this approach may include the integration of

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machine learning methods to automate the process of selecting optimal model parameters and predicting product quality based on an extended set of input data.

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