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METHODS FOR WOOD CUTTER OPTIMISATION AND QUALITY ASSESSMENT USING BENCH SIMULATION AND MATHEMATICAL MODELLING. 1. ALGORITHM FOR SOLVING THE PROBLEM OF OPTIMISING PREFABRICATED TOOL DESIGN USING PHYSICAL AND MATHEMATICAL MODELLING*

This paper outlines practical ways to ensure the efficiency and quality of prefabricated wood cutters at the process engineering phase.

Key words: woodworking, prefabricated cutters, physical and mathematical model, optimisation, reliability, finish quality.

When it comes to choosing specific cutting tools (most notably cutters), the efficiency of wood machining processes, for example, in furniture-making, which relies on flexible automation tools, is governed by the specificity of production. For wood-based materials, this specificity is in the anisotropy of the material properties defined by the fibre texture of the wood and by the presence of local inclusions (knots) whose physical and mechanical properties vary significantly from the rest of the material. Other materials used in furniture making, chiefly the chip plates, are also characterised by certain specifics of processing.

From the perspective of ensuring tool reliability and product quality, the above influences demonstrate the need to identify the principles of cutting processes and develop a physical and mathematical model based on such principles. Absence at this time of a uniform economic optimisation model proves that the choice of a target function and limitations on its parameters during optimisation of a wood machining process cannot be the same every time and depends, in each particular case, on the requirements on the surface finish quality, the output, the durability period or the tools' service life.

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It seems clear that the issues of ensuring precision and instrumental efficiency and reliability of wood machining processes must be addressed throughout the lifecycle of the tools, from engineering to operation. Furthermore, if tool precision is an issue that can be dealt with, the reliability issue presents the most significant challenge. This is because the classic criteria for the mathematical theory of reliability, i.e., service life and durability (see OST2-N06-23–82), used to evaluate a tool presume the need for cutting trials and statistical manipulation of the trial data, which means they require significant time and cost. This entails a need for other criteria, in addition to the classic ones, such as the concept of reliability of complex systems [15]. Some of these criteria come into use in engineering: the quick test concept has certain drawbacks (cutting conditions differ from real-life conditions) and does not rule out the laborious trial-and-error method during the search for optimal solutions; diagnostics and monitoring enable assessment of reliability based on such proxy measures as hardness, spectral response, heating temperature and reparability. We have to admit that the development and industrial deployment of these concepts are not proceeding fast enough for the reasons described below.

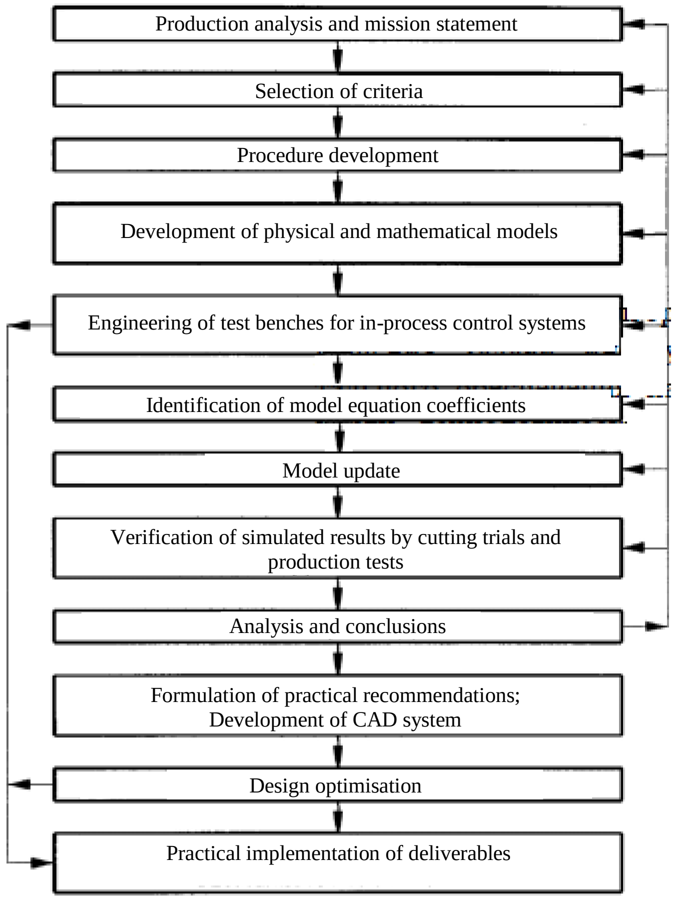

Fig. 1. Flow chart for the process reliability instrumental assurance algorithm

At the engineering phase, the challenges are often explained by the lack of a uniform integrated model that considers all the influences of the cutting process and the absence of a definite correlation between these individual influences and the reliability criteria. Moreover, this model must take into account the influence of the process system itself, whereby the assumptions made by some prominent experts in the past that a tool's performance efficiency does not depend on the properties of the process system are untenable, as is demonstrated by real-life experience. On top of everything, a decrease in hardness of the process system might cause durability of tools made from brittle materials (composites) to decline by as much as 400%. The current understanding of a machine tooling unit as a system with a closed-loop energy cycle is also wrong because the cutting process involves a change of mass due to wear on the tool, as well as dissipation of heat in space due to convection and chip heating and disposal. This is why development of a model under the uniform energy theory and practical implementation of the instrumental assurance of process reliability are burning issues that must be addressed immediately. In the existing situation, these challenges may be addressed step by step, by complicating and developing models in accordance with the algorithm provided in Fig. 1 [8].

At first sight, the original model may be represented by a dynamic model that ties together the individual elements of the process system and evaluates their reliability based on static and dynamic hardness, impedance, admittance or other parameters (Fig. 2) using the identified correlations [12].

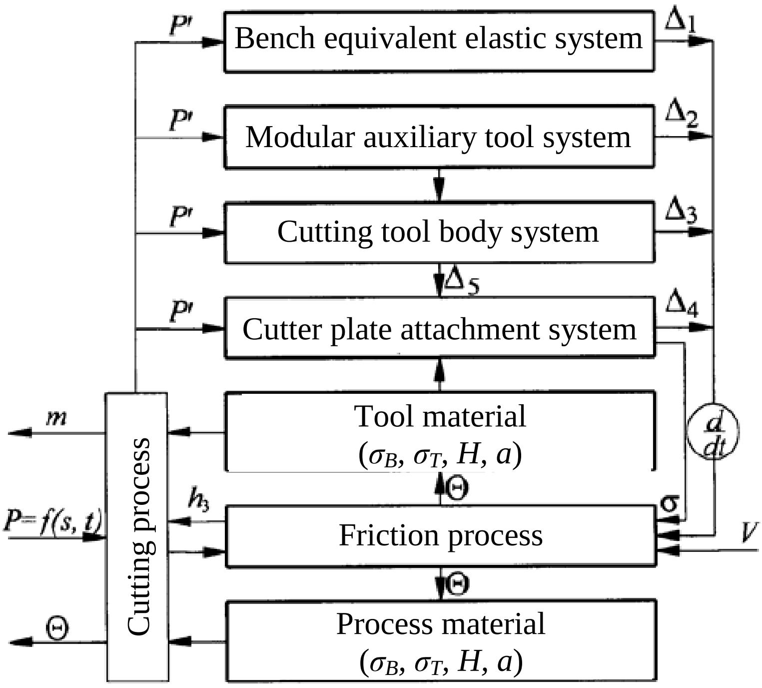

Fig. 2. Dynamic model of a process system (PS): *V, S, t* – cutting modes; σ_{Bi}, σ_{Ti}, *H, a* – mechanical properties of the tool and process materials; Δ_i – PS elastic strain; *m, Θ* – chip mass and heat; *P* and *P′* – simulated and true cutting forces; *σ* – stress

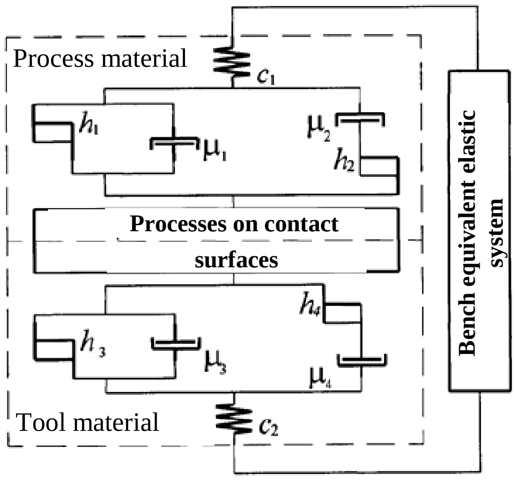

Fig. 3. Rheological durability model of the cutting tool: h_i – dry friction coefficient; μ_i – viscous friction coefficient; c_i – static hardness coefficient

Moreover, if these are obviously the principal parameters for the modular auxiliary tool, the research results indicate that, in the case of a prefabricated cutting tool subsystem, there is no definitive answer, which leaves the chance of errors in the choice of the design concept. A higher level of confidence may be achieved by using the rheological model of the cutting process (Fig. 3), which helps evaluate the tool through the established characteristic of durability, depending, first, on the correlation of the mechanical properties of the tool material and the process material and, second, on that between the tool material's breaking strength and yield point, on one hand, and the stress in the cutter plate, on the other hand [11]:

$$T = C_T(\sigma_B/\sigma)^x\ (\sigma_T/\sigma)^y\ (H_t/H_p)^z\ (a_t/a_p)^q\ (K_1\ K_2\ \ldots\ K_n),$$

where T – tool's durability period;
C_T – cutting value;
σ_B, σ_T – breaking strength and yield point of the tool material;
σ – stress in the cutter plate;
H_t and H_p – hardness of the tool and process materials, respectively;
a_t and a_p – resilience of the tool and process materials, respectively;
$K_1, K_2, \ldots, K_n$ – coefficients of influence of the cutting conditions.

The most challenging job is to determine the mechanical performance of materials at a given heating temperature corresponding to the preset cutting mode. To cope with this challenge, one must possess experimental results, which, in turn, requires performance of fundamental studies that take a lot of time. This is why the initial assessment of the cutting tool quality can rely on the models of strain precision and stressed state of the cutter plate [1, 6, 7, 9], and the probability of assessment results may be increased with the help of other known models: static [3], dynamic [4, 14] and thermophysical [10]. An alternative to the rheological model is a more complex tribotechnical model that can also be used to predict the tool's durability period:

$$T = \frac{\left(\frac{h_3 \cos\gamma \sin\alpha}{\cos(\alpha+\gamma)}\right)}{C\left(\frac{P_a\theta}{K_v}\right)^{1+\beta t}\Delta^{1-\beta}\left(\frac{K_f}{\sigma_0\theta}\right)^{t}(\eta_{ca})^{-\beta t}V},$$

where h_3 – width of wear band on the rear surface;
γ, α – front and rear cutting angles;
$C = v^{0.5}\ \Gamma(v)\ \Gamma(1 + t/2)[4(v + 1)\ \Gamma(v) + t/2]^{-1}$;
v – power approximation of the starting section of the supporting curve;
Γ – gamma function;
t, σ_0 – parameters of material friction fatigue;
P_a – nominal pressure;
θ – constant elasticity of the tool material, $\theta = (1 - \mu^2)/E$;
μ – Poisson's constant;
E – modulus of elasticity;
K_v – temperature influence coefficient;
$B = 1/(2v + 1)$;
$K_f = 2(4f^2(1 - \mu + \mu^2) + (1 - 2\ \mu)^{0.5} / \pi$ if $\sigma_B^{ten} \approx \sigma_B^{com}$
$K_f = 4f(1 + \mu^2) / \pi$ if $\sigma_{br}^{ten} \approx \sigma_{br}^{com} << 1$;
f – friction coefficient;
σ_{br}^{ten}, σ_{br}^{com} – material's breaking strength (tensile and compressive);
η_{ca} – coefficient of discrepancy between the contour area of contact A_c and nominal area of contact A_a, $\eta_{ca} = A_c/A_a$;
V – rate of cutting.

The challenges of developing this kind of model are similar to those listed above. The bottleneck is to identify the measures of mechanical properties of surfaces that differ greatly from the data obtained during specimen tests. One possible option is to use integral assessment of tool quality. Today, the above models may be considered as the cutting tool's CAD foundation built in accordance with the modular principle [13]. As the uniform model develops, this approach will enable its continuous complication by introduction of new modules without readjustment of its structure; it will also allow its individual elements to be used to resolve some specific problems.

During manufacture and operation of the tool, the problem can be resolved through the development of in-process control diagnostic and test benches [2, 5]. These test benches must be developed in accordance with the same principles and in reliance on the same assessment criteria as those used in the mathematical models. At the tool manufacture phase, such test benches are employed for outgoing inspection of reliability and, at the operation phase, for incoming inspection. In both cases, the test benches help control the quality of manufacture of individual elements and tool assembly in general, identify the causes of flaws, use the common durability correlations to adjust the cutting rate for ensuring the designed durability period and perform selective sampling of tools in a product batch. Such bench tests are known as in-process control methods and experience has proven them to be very effective in assessing the quality of a tool's design, but they cannot be used to detect hidden flaws in the cutter plate. In addition, cutting is in many respects a random process, which is explained, for example, by inhomogeneity of the structure and, consequently, properties of the processed materials due to presence of various inclusions in such materials. This is why final resolution of the issue of instrumental assurance of machining process reliability is impossible without employing facilities that monitor the condition of the tool's cutting edge in the process of cutting. There is also a need for express methods for finding optimal cutting modes that rely on certain physical characteristics of the cutting process (forces, vibrations, acoustic emission, temperature and thermal electromotive force gradient [5]).

From the standpoint of ensuring the desired precision and performance efficiency, the existing composite surface machining processes require substantial labour input and consist of multiple initial tuning and intermediate inspection operations. Complex positional relations between the reference axes of the machined surfaces and the body of the end product introduce complications to the process preparation stage, i.e., tuning of the bench, accessories, tool and templates. The equipment, tools and accessories used at this time make it impossible to avoid labour-intensive manual finishing operations completely.

The desired product precision is a direct result of the surface shaping precision and the deformations that develop in the process of machining. This challenge is addressed with the help of a geometrical model of the shaping process (includes deformations analysis). The temporal properties that are used, for instance, in the shaping performance analysis, are addressed integrally.

The technique in question employs geometrical interpretation and time as one of the generalised coordinates. The kinematic chain of the process system is closed by the force-time characteristic determined through geometry analysis of instant cross-sections of the layer being cut. Fig. 4 below shows the corresponding diagram of variation of the cut layer thickness due to deformations and the structural diagram exemplified by the dynamic model of the milling process, which can be used as a general diagram [1, 14].

An elastic process system is shown as an equivalent dual-mass system of the tool and the blank that oscillates in three mutually perpendicular directions. Equivalent elastic systems (EES) of the blank and the tool are characterised by masses *m* reduced to the cutting zone, generalised coefficients of resistance (damping) λ and hardness *k*, which are normally different in three coordinate directions. The system is closed. Its closed state is determined by the interaction between the blank and tool EES and the cutting process, and the system's multi-loop structure is explained by the fact that several cutter bits are involved in the cutting process. Both EES interact with each other through the cutting process, whose action is replaced by the summary elements of the cutting force $\left(\sum_{i=1}^{N_p} F_{Z_i};\sum_{i=1}^{N_p} F_{Y_i};\sum_{i=1}^{N_p} F_{X_i}\right)$ resulting from the action of the cutter bits involved in the cutting process at a given time (N_p is variable due to inconsistency of the milling process).

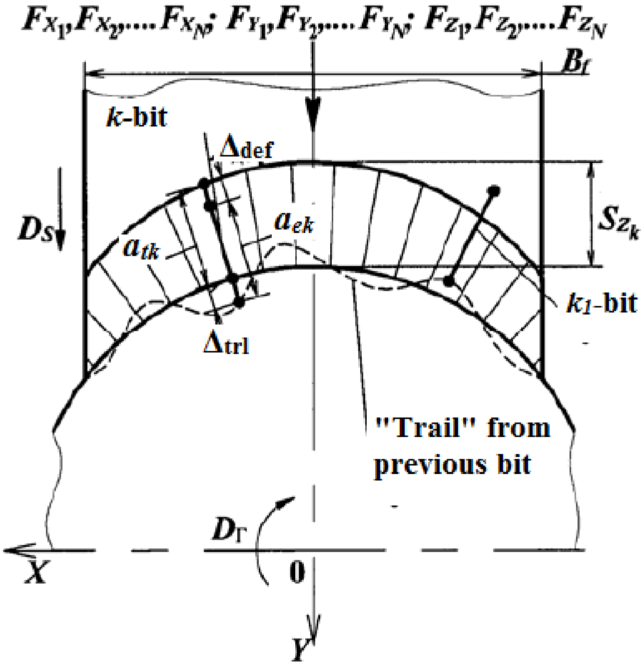

Fig. 4. Variation of thickness layer due to PS deformation: a_{tk} – layer thickness on k-bit conditional upon system tuning; a_{ek} – effective cut thickness on k-bit; Δ_{def} – variation of cut thickness due to deformation under the influence of cutting force; Δ_{trl} – same, resulting from the pass of previous bit (‘trail’).

These forces that act on the cutter bits were obtained by reducing to the *OXYZ* fixed coordinate system of the forces from the coordinate system of the rotary cutter: F_{t1}, F_{t2}, …, F_{tN} – tangential components on *k*-bit; F_{r1}, F_{r2}, …, F_{rN} – radial components on *k*-bit; F_{o1}, F_{o2}, …, F_{oN} – axial components on *k*-bit.

Components of the cutting force in a moving coordinate system result from the material’s resistance to cutting; they depend on the effective cross-section area of the cut layer and are functions of time: $S_1(t)$, $S_2(t)$, …, $S_N(t)$.

The effective cross-section of the cut layer is a product of the effective thickness $\bar{a}_1(t)$, $\bar{a}_2(t)$, …, $\bar{a}_N(t)$ and the effective width $\bar{b}_1(t)$, $\bar{b}_2(t)$, …, $\bar{b}_N(t)$ of the cut layer.

The effective thickness and width of the cross-section of cut on the *k* operational bit depend on the system tuning to the pre-set (kinematic) thickness and width of the cross-section of cut, as well as on its variation as a result of mutual deformations of the system under the influence of the operational bits and the machining ‘trail’ from the previous bit.

The computation process is as follows. In the initial stages, analysis of the geometry parameters of the machined surface is used to select the surface shaping profile: identification of the tool’s generating surface and feed motions. The shaping function is built bearing in mind the limitations of the machine. Analysis of the cutting surface envelopes is used to determine whether the selected cutting profile meets the precision requirements applied to the surface profile.

The tool’s structural parameters (number of bits, geometry, etc.) are determined for the selected generating surface of the tool. The selected structural parameters of the tool and its operating behaviour (main motion and feed motion), as well as blank geometry details, are used to calculate the instant characteristics of cross-section of the cut layer (thickness and width), which is followed by stepwise building of the vector functions of cutting forces.

The next step in the computation process is to generate information about the yield margins of the process system (PS) elements located immediately next to the cutting zone and about their dissipation and inertial characteristics. Static and dynamic discrepancies of the parameters of cut layer cross-section are determined based on the selected machining profile and structural parameters of the tool. Effective cutting surfaces are reproduced bearing in mind the elasticity of the PS elements and their envelopes to assess the shape and dimensions of the machine surface, the error is determined and the decision is made whether or not to compensate the error. Where necessary, the parameters or the shaping function are adjusted as appropriate.

Under the given kinematic conditions, finding the optimal form, type and structural design of the tool in combination with manipulation of the stock cutting pattern enables optimisation of strain distribution during the machining process and guarantees the desired shaping precision and machining efficiency.

Consistent with the traditional shaping theory, this model uses a mathematical apparatus that relies on parametric matrix transformations. Time is selected as the key parameter. The model also allows the dynamic attributes of the process in the frequency domain to be analysed.

Conclusions

1. The suggested approach enables formulation of requirements on the structural design of the cutting tool, its operating conditions and engineering (also using CAD tools) of the process operation of wood machining as early as at the process design phase, which helps increase precision and performance efficiency under existing process limitations.

2. Final resolution of the problem of instrumental assurance of reliability, performance efficiency and precision of machining processes in both woodworking and other industries is only possible given an integrated approach and depends chiefly on evolution of physical models and processes that occur in the cutting zone and inside the cutting tool.

3. The reliability and precision of the machining must be assessed on the basis of both direct (durability, service life, strength) and indirect criteria (stress-strain state, static hardness, dynamic behaviour (resilience, impedance, admittance, spectral response level), the correlation of mechanical properties of the tool material and process material under given cutting temperature), as well as on the basis of other criteria that are correlated with the direct criteria of reliability.

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