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THEORETICAL BASIS FOR THE DEVELOPMENT OF AN ALGORITHMIC UNIFIED COMPLEX OF MATHEMATICAL MODELS OF CUTTING FORCES

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Abstract: In the article for practical application within the framework of creating a matrix theory of accuracy of multi-tool machining for a range of multi-tool adjustments (tool setups) of previously developed models of machining error, the necessity of dependence of the coordinate components of cutting forces on technological factors is shown. (parameters of cutting conditions, strength properties of the material being machined, deformation properties of the technological system, etc.). For this purpose, the tasks of cutting force models are established, a systematics of machining schemes used on modern lathes is carried out, highlighting two schemes for the formation of a machined surface (trajectory and profile), and the principles for developing cutting force models are given. Thus, the development of an algorithmic unified complex of mathematical models of cutting forces is substantiated, taking into account the introduced systematics of machining schemes according to the mechanism of formation of the machined surface.

Keywords: *Multi-tool machining, Multi-tool adjustment, Systematics of machining schemes, empirical and analytical models, cutting force models, mathematical models of cutting forces.*

Introduction. As part of the creation of a matrix theory of the accuracy of multi-tool machining [1-17], for a range of multi-tool adjustments, two classes of error models for the dimensions performed have been developed:

-a generalized analytical model of distortion of performed dimensions (for the entire set of multi-tool adjustments performed on automated machines of the turning group);

-models of scattering fields of dimensions performed in multi-tool adjustment.

-In turn, scattering field models are subdivided into two types according to the methodology:

-analytical models (for homogeneous multi-tool adjustments - tools of the same type in setup);

-simulation stochastic models (for non-homogeneous multi-tool adjustments - different types of tools in setup, for example, cutters and drills).

In all the listed categories of machining error models, the connection between the error and the technological conditions of machining is carried out through the components of the cutting forces.

Thus, for the practical application of the machining error models developed in [1-17], the dependences of the coordinate components of the cutting forces on technological factors are necessary (parameters of cutting conditions, strength properties of the material being machined, deformation properties of the technological system, etc.). These dependencies establish the so-called cutting force models.

Tasks of Cutting Force Models. The main task of cutting force models, when applied in the developed theory of machining accuracy, is the most complete account of the entire set of factors that determine the magnitude and direction of the cutting force for each used cutting tool and the conditions for its use.

A.A. Koshin's plane-parallel accuracy theory [18] of multi-tool machining is based on traditional empirical power dependences for the components of cutting forces. Machining error models in the proposed matrix theory of accuracy [1-17] are also formed using power dependences for the components of cutting forces:

$$P_z = C_{p_z} t^{x_{p_z}} S^{y_{p_z}} V^{z_{p_z}} K_{p_z} \text{; where } K_{p_z} = K_{\varphi p_z} K_{\gamma p_z} K_{\lambda p_z} K_{M p_z} K_{r p_z}$$
$$P_y = C_{p_y} t^{x_{py}} S^{y_{py}} V^{z_{py}} K_{p_y} \text{; where } K_{p_y} = K_{\varphi p_y} K_{\gamma p_y} K_{\lambda p_y} K_{M p_y} K_{r p_y} \quad (1)$$
$$P_x = C_{p_x} t^{x_{p_x}} S^{y_{p_x}} V^{z_{p_x}} K_{p_x} \text{; where } K_{p_x} = K_{\varphi p_x} K_{\gamma p_x} K_{\lambda p_x} K_{M p_x} K_{r p_x}$$

These dependencies reflect the influence of almost all of the factors mentioned above. Cutting condition parameters t, s and v are taken into account directly. The geometry of the cutting tool is taken into account by means of correction factors $K_{\gamma p_i}$, $K_{\alpha p_i}$, $K_{\varphi p_i}$, $K_{\varphi_1 p_i}$, $K_{r p_i}$ (*i*=*x*, *y*, *z*). The type of cutting and machined materials is determined by the coefficient C_{p_i} (*i*=*x*, *y*, *z*). The hardness of the processed material is given by the coefficient $K_{M p_i}$ (*i*=*x*, *y*, *z*).

In the special and reference literature there are tables of values of the main parameters C_p, exponents x_p, y_p, z_p and correction factors $K_{Mp}, K_{\varphi p}, K_{\gamma p}, K_{\lambda p}, K_{rp}$ for common and well-studied cutting conditions [19].

It should be noted that the coordinate components of the cutting force, determined by formulas (1), are specified in the tool coordinate system generally accepted in cutting theory. The *Y* axis is directed normal to the surface to be machined (for a through cutter, this is the tool axis, for a boring cutter, it is normal to it). The *X* axis is oriented along the feed vector. The *Z* axis is perpendicular to the *XY* plane.

For single-coordinate machining, when the feed vector S is directed along one of the coordinate axes of the machine coordinate system, the components of the cutting forces calculated from the dependencies (1) are trivially consistent with the machine coordinate system, in which the errors of the performed dimensions are calculated in the theory of accuracy. For longitudinal turning, the coordinate systems of the tool and the machine are the same, therefore, from formulas (1), we directly obtain the normal component P_y, the tangential P_z, and the component in the direction of the feed vector (for longitudinal turning, this is the axial component P_x). In transverse turning, the normal to the machined surface is directed along the *X* axis of the machine, therefore, P_y calculated by (1) is directed along the *X* axis of the machine, P_x from (1) is directed along the *Y* axis of the machine.

Machining, when the feed vector is directed along one of the coordinate axes of the machine coordinate system, is typical for traditional universal lathes, as well as for cam-controlled automatic machines (multi-spindle and turret-automatic and semi-automatic). Modern CNC machines of the turning group are characterized by spatial adjustments, when the axes of the tool and machine coordinate systems, as well as the feed vector, are arbitrarily oriented relative to each other in space. Therefore, in the models of cutting forces, this mutual spatial orientation of the tool and machine coordinate systems, as well as the direction of the feed vector, must be taken into account.

As a result, many determining factors for cutting forces can be divided into the following three groups:

-cutting tool characteristic (cutting material, rake angle γ, clearance angle α, nose radius r, side cutting edge angle φ, end cutting edge angle φ_1);

-properties of the material to be machined (strength characteristics – HB, HRC, σ_B, σ_T, surface condition);

-technological factors (amount s and direction e_s of feed S, cutting speed v and depth of cut t, cutting tool orientation e_u).

In addition, stochastic characteristics of the initial parameters are necessary for models of scattering fields of the dimensions performed. In cutting force models, this is, first of all, the magnitude of the scattering of the strength properties of the material being machined (for example, ΔHB) and the range of fluctuations in the depth of cut Δt.

Another, and perhaps the main, task of developing a complex of cutting force models is the mandatory coverage of the entire range of cutting schemes applicable on modern lathes.

Systematics of Machining Schemes. The analysis of multi-tool and single-tool adjustments on modern lathes of the turning group, carried out in [1], showed that there are two different schemes for the formation of a machining error due to different mechanisms for the formation of a machined surface.

It is possible to distinguish two basics, from the standpoint of the mechanism of formation of the machined surface, machining schemes - trajectory and profile. (see Table 1).

Table 1. Basic machining schemes from the point of view of the mechanism of formation of the machined surface

Machining scheme name	Description of the machining scheme	Machining scheme type
Trajectory	The machined surface is formed as a result of moving the cutting tool tip along some given trajectory, while the tool trajectory is a generatrix for the formed surface - a body of revolution.	1
Profile	The machined surface is formed as a result of copying the profile of the cutting tool, i.e. the profile of the tool is a generatrix for the formed surface - the body of revolution.	2

The distribution of the nomenclature of technological transitions for the type of cutting tools on modern lathes of the turning group according to the selected types of machining schemes (Table 1) is given in Table. 2.

Principles for Developing Cutting Force Models. The analysis of existing mathematical models of cutting forces showed that the methodologies for creating a variety of existing models of cutting forces are divided into two types: empirical and analytical. Each of the selected types has a significant number of models developed for various cutting patterns. Table 2 shows the availability of cutting force models for machining schemes for the type of cutting tools on machines of the turning group.

As follows from Table 2, out of the entire set of positions of the cutting tool codifier (21 positions) used in turning, only 5 are provided with cutting force models in full. There are both empirical and analytical models for them. 9 positions, i.e. 42% of tools are not fully provided with cutting force models, there are not even empirical models. 7 positions, i.e. 33% of cutting tools are provided with models at the initial level - there are only the simplest empirical models that reflect typical machining conditions.

Turning on modern automatic machines provides for the simultaneous participation in the adjustment of several different types of cutters [1, 2, 20] - turning, facing, forming, chamfering, boring, cut-off, grooving, wide, chamfering boring. There is also an extensive range of cutters for CNC machines (carbide prefabricated with mechanical fastening of polyhedral inserts). These are turning tool for contour turning, boring tool, grooving tool. The work of the listed types of cutters refers to various cutting patterns: orthogonal and oblique, free and not free. Therefore, it is necessary to have mathematical models that allow calculating the values of the cutting force components in the direction of the main coordinate axes for various types of turning tools in a wide range of variation of technological factors.

Until now, to calculate the forces when cutting metals, empirical dependencies are used, which provide quite sufficient accuracy for practice. On their basis, normative materials are developed according to cutting conditions. However, in order to obtain empirical dependencies for each material being machined, it is necessary to carry out special experiments, which, due to the large number of factors affecting the cutting forces, turn out to be quite numerous and laborious.

Table 2. Availability of cutting force models for machining schemes for the type of cutting tools on lathes

Type of cutting tool	Models		Type of machining scheme
	Empirical	Analytical	
Turning tool	+	+	1
Chamfer cutter	-	-	2
Grooving cutter	+	-	2
Wide cutter	-	-	2
Form tool	-	-	2
Knurling tool	-	-	
Boring tool	+	+	1
Boring chamfer cutter	-	-	2
Facing tool	+	+	1
Cut-off tool	+ ($\varphi=\pi/2$)	-	2
Drill-centering tool	-	-	2_o
Drill	+	-	1_o
Core-drill	+	-	1_o
Countersink	+	-	2_o
Reamer	+	-	1_o
Thread cutter	+	-	2
Turning tool made for CNC machines	+	+	1
Contour cutter with multifaceted insert for CNC machines	-	-	1
Boring cutter made for CNC machines	+	+	1
Thread cutter with multifaceted insert for CNC machines	-	-	2
Grooving cutter made for CNC machines	-	-	2

In addition, empirical models are subjective in form and set of variables and, therefore, have a number of significant drawbacks. The nature of dependencies, as a rule, is taken from the conditions of their greatest simplicity. Because of this, power-law models are most often used, although the real curves describing force dependences are complex, often extremal.

The modern concept of metal cutting is based on the position that this process is a kind of elastic-plastic deformation process. Such processes are mathematically described, which is a prerequisite for the analytical determination of cutting forces.

In principle, for the theory of machining accuracy, it does not matter what the nature of the mathematical model of cutting forces is - empirical or analytical. It is important that it reliably reflects all the necessary patterns of the cutting process and the influence of control factors - cutting conditions.

In [1], the problem was posed and, in relation to multi-tool machining on modern lathes, an algorithmically unified complex of error models for the dimensions performed was developed. To ensure the algorithmic unity of the developed theory of accuracy of multi-tool machining, it is necessary that the complex of mathematical models of cutting forces be algorithmically unified.

Conclusions. Two schemes for the formation of machined surface are distinguished: trajectory and profile. It is substantiated that the most effective way to ensure algorithmic unity is the development of analytical models of cutting forces, taking into account the introduced systematics of machining schemes according to the mechanism of formation of machined surface. The developed set of force models will allow using the obtained accuracy models for all adjustments from the classifier of multi-tool adjustments.

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