Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2024 vol. 26 no. 4 pp. 92–111
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2024-26.4-92-111

NSTU NETI

Obrabotka metallov - Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Systematics of multi-tool setup on lathe group machines

Nizami Yusubov [a, *], *Heyran Abbasova* [b]

Department of Machine Building, Azerbaijan Technical University, 25 H. Cavid avenue, Baku, AZ1073, Azerbaijan

[a] https://orcid.org/0000-0002-6009-9909, nizami.yusubov@aztu.edu.az; [b] https://orcid.org/0000-0002-0407-5275, abbasova.heyran@aztu.edu.az

ARTICLE INFO

Article history:
Received: 17 July 2024
Revised: 19 August 2024
Accepted: 17 September 2024
Available online: 15 December 2024

Keywords:
Systematics of multi-tool setup
Lathe group machines
Classification formula for setup
Parallel multi-tool machining
Single-carriage two-coordinate setups
Two-carriage two-coordinate setups

Funding
This work was supported by the Azerbaijan Science Foundation - Grant № AEF-MGC-2024-2(50)-16/01/1-M-01.

ABSTRACT

Introduction. The analysis of factory lathe-automatic operations revealed a significant variety of multi-tool setups and identified its areas of application. To develop a matrix theory of accuracy for multi-tool machining and create a unified algorithmic approach to errors modeling for all possible spatial multi-tool setups, it is necessary to consider the flexibility of the technological system in all coordinate directions. In this regard, it is required to systematize a large number of existing multi-tool setups and classify it to structure the information and improve the understanding of its application. **Purpose of the work** is to develop a classification of multi-tool setups on multi-carriage and multi-spindle *CNC* lathes, enabling the creation of both a matrix model of machining accuracy for each classification class and a unified generalized matrix model of machining accuracy for the entire classification class. **The work investigates** the systematics of multi-tool setups, oriented toward the development of matrix models of machining accuracy. Therefore, the classification considered in this work is aimed at identifying the characteristics of force loading and deformation of the technological system during multi-tool machining. **The research methods** involve identifying the parameters used for classification and the hierarchy of these parameters, which determines the levels and order of the systematics. Based on the principles of systematics of multi-tool setups used in traditional automatic lathes, an analysis of its adaptation to the capabilities of modern lathes designed for multi-tool machining is conducted. **Results and discussion.** As a result of the research, a formalized six-level classification of multi-tool setups is developed, which includes the following aspects: the method of workpiece mounting, the set of carriages, the types of cutting tools, the types and directions of carriage feeds, the orientation of cutting tools relative to the workpiece, and the method of tool engagement (parallel, sequential). This classification takes into account the technological capabilities for organizing multi-tool machining on modern *CNC* lathes. The main classes of the proposed systematics of multi-tool setups in the presented work include single-carriage single-coordinate setups, single-carriage two-coordinate setups, dual-carriage single-coordinate setups, dual-carriage two-coordinate setups, and multi-carriage setups. The proposed systematics of multi-tool setups on lathe group machines is aimed at developing machining accuracy models and can serve as a basis for developing recommendations on cutting modes for these *CNC* machines. The proposed classification of multi-tool setups forms the foundation of the methodological support for the *CAD* system of lathe-automatic operations and serves as the basis for creating next-generation *CAD* systems for lathe operations.

For citation: Yusubov N.D., Abbasova H.M. Systematics of multi-tool setup on lathe group machines. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2024, vol. 26, no. 4, pp. 92–111. DOI: 10.17212/1994-6309-2024-26.4-92-111. (In Russian).

Introduction

Multi-tool machining is one of the most effective means of increasing the productivity of machine operations in machine building industry. [1–10]. It should be noted that the functions of metal-cutting machine tools are constantly expanding to meet the demands for high productivity and precision when machining complex and hard-to-process parts on a single machine [1–6, 11–20]. For example, the paper [2] provides a comprehensive review of multifunctional machines used for metal cutting, its kinematic configurations, control technologies, and programming. The paper [8] addresses the issue of optimizing

*** Corresponding author**
Yusubov Nizami D., D.Sc. (Engineering), Professor
Azerbaijan Technical University,
25 H. Javid avenue,
AZ 1073, Baku, Azerbaijan
Tel.: +994 (55) 324 50 12, **e-mail:** nizami.yusubov@aztu.edu.az

cutting parameters on multi-position machines and automated lines equipped with multi-spindle heads. In the work [14], turning was performed on a lathe with two cutting tools mounted on the carriage, one in the front and the other in the back. A number of studies [21–34] have addressed specific issues related to the problems of designing multi-tool machining or optimizing the process technology. In the work [30], the opportunity of applying various modeling and optimization methods in metal machining processes, classified by several criteria, was critically evaluated. However, none of these studies have examined the need to organize multiple multi-tool setups, or introduced a system for its analysis. In other words, it has not addressed the classification of multi-tool setups and the creation of a unified algorithmic model for machining errors for the entire set of spatial multi-tool setups, taking into account the compliance of the technological system in all coordinate directions.

The machining error component that arises due to the elastic displacements of the elements of the technological system under the influence of cutting forces, often referred to as the deformation component, is the most controllable during machining and at the design stage. By varying cutting conditions, cutting tool geometry, initial error (at an intermediate stage of machining), and changing the material of the cutting part, it is possible to significantly influence the magnitude of machining error [4, 9, 13, 15, 16, 25, 26, 33]. Therefore, the mathematical model of the deformation component of machining error forms the basis of the computational matrix theory of machining accuracy [13, 14, 15, 25, 26, 33, 35, 37].

Attempts to systematize multi-tool setups can be found in the works of *A. A. Koshin* [35–36]. He introduced four main and one additional classification levels for setups. The main classification criteria are the type of carriage, the type of cutting tool, its orientation (whether it presses the workpiece toward or away from the carriage), and the method of workpiece mounting. The additional criterion is the type of auxiliary device mounted on the main carriage. However, there is no way to describe a number of features specific to multi-tool machining on modern *CNC* (*Computer Numerical Control*) machines.

The formalized systematization of multi-tool setups forms the basis of the methodological support for the *Computer-Aided Design* (*CAD*) system of turning-automatic operations [37]. Modern automatic machines, designed for multi-tool machining and equipped with *CNC* systems, offer significantly richer technological capabilities for organizing multi-tool operations. Therefore, a new, more multifactorial systematization of multi-tool setups, reflecting these new capabilities, is required.

The purpose of the work is to develop a classification of multi-tool setups on multi-carriage and multi-spindle *CNC* lathes, enabling the creation of both a matrix model of machining accuracy for each classification class and a unified generalized matrix model of machining accuracy for the entire classification class.

To achieve the set purpose the following tasks are solved:

1. The principles of classification of multi-tool setups are revealed;
2. The main classes of the proposed systematics of multi-tool setups are defined.

Research methodology

Principles for classifying multi-tool setups

The basis of systematics is a set of classification indicators. Taking as a basis the principles of the systematics of multi-tool setups on traditional automatic lathes [37], we will consider the transformation of indicators to the capabilities of modern lathes of the turning group, focused on multi-tool machining.

The key issue of systematics is to identify the parameters by which the classification is carried out, and the hierarchy of these parameters, which determines the levels and order of systematics. The proposed systematics of multi-tool setups is focused on the development of models of machining accuracy.

The main feature of multi-tool machining is the force interaction between the tools in the setups [31, 32]. Therefore, the classification is aimed at identifying the characteristics of force loading and deformation of the technological system during multi-tool machining.

The basis of the scheme of deformation of the technological system under force loading during machining is the method of fixing the workpiece. It is a common, single indicator for multi-tool setups. The mounting method largely determines the possible types of tools and its placement in the setup. Therefore, it is logical to put this indicator at the first level of classification of multi-tool setups [31, 32].

Next, it is necessary to describe the types of cutting tools in the setup and its placement relative to the workpiece and each other, i.e. describe the setup structure itself. The basis of the structure of multi-tool setup is a set of carriages on which the tools are placed. Therefore, at the second level of classification, there should be a description of the carriages involved in the setup.

The third level is a description of the actual cutting tools that form the setup.

The introduced three factors describe the type of cutting tools and its location. However, the force effect of the tools on the workpiece is determined by the cutting forces, the values of which and the direction of action are determined by another factor – the feed direction. The feed movement refers to the carriage, so it is advisable to attribute this factor, as an additional one, to the description of the carriage.

In multi-tool setups, it is not uncommon for a cutting tool to be rotated relative to the base surfaces of the carriage with the help of special holders. Therefore, an indicator of the orientation of the tool relative to the base of the carriage, or workpiece is introduced.

The classification of multi-tool setups on traditional automatic lathes covers setups where the tools are working simultaneously. However, modern *CNC* machines equipped with a tool magazine allow organizing multi-tool machining with sequential use of tools. Having a single technological base and working from a common control program, these setups are subject to the laws of multi-tool machining, in the traditional sense of the term. Moreover, the machining accuracy models make it possible to take into account technological heredity and reach the design of multi-transition machining. Therefore, it is proposed to expand the concept of multi-tool setup, including setup both with simultaneous operation of tools and with sequential operation.

Thus, we get 6 levels of classification of multi-tool adjustments (method of mounting the workpiece, set of carriages, type of cutting tools, types and directions of feed of the carriages, orientation of the cutting tools relative to the workpiece, method of including tools in the work (parallel, sequential)).

Summarizing the principles of classification of multi-tool setups taking into account the conditions of modern *CNC* lathes, it is possible to develop a corresponding classification formula:

$$H \equiv Yk_y \bigcup_i \left\{ \bigcap_j \left[C_{ij} k_c(e_c) S_{ij} k_s(e_s) \left[\bigcap_k u_{ijk} k_u(e_u) \right] \right] \right\}, \tag{1}$$

where $\boldsymbol{Y}$ is the installation method sign; $\boldsymbol{k_y}$ is the installation method code; $\boldsymbol{C_{ij}}$ is the carriage sign; $\boldsymbol{k_c}$ is the carriage type code; $\boldsymbol{e_c}$ is the carriage location; $\boldsymbol{S_{ij}}$ is the carriage feed sign; $\boldsymbol{k_s}$ is the carriage feed type code; $\boldsymbol{e_s}$ is the carriage feed direction; $\boldsymbol{u_{ijk}}$ is the cutting tool sign; $\boldsymbol{k_u}$ is the cutting tool code; $\boldsymbol{e_u}$ is the cutting tool orientation; $\boldsymbol{k}$ is the number of cutting tool on this carriage; $\boldsymbol{j}$ is the carriage number at this working position; $\boldsymbol{i}$ is the working position number; $\cap_k$ is the sign of parallel (simultaneous) operation of the tools described in square brackets after this sign; $\cap_j$ is the sign of parallel (simultaneous) operation of carriages described in square brackets after this sign; $\boldsymbol{U_i}$ is the sign of consistent development of all working positions.

For traditional multi-spindle lathes, the concept of a working position coincides with the generally accepted one. With regard to modern multi-tool *CNC* machines, it is advisable to expand the concept of a working position. Double-carriage *CNC* machines equipped with a tool magazine allow to organize a series of successive elementary setups with the simultaneous operation of several tools. Thus, on a modern *CNC* machine, a sequential execution of a set of multi-tool setups, understood in the traditional sense, can be organized. Since the apparatus of the computational theory of accuracy of multi-tool machining [31, 32] makes it possible to analyze such a sequence of multi-tool setups, it makes sense to introduce into consideration a generalized multi-tool setup, which includes a time-distributed sequence of traditional multi-tool setups with simultaneous operation of several tools. Each stage of the work of such a generalized setup, related to a separate set of simultaneously working tools, is proposed to be called the position of a generalized multi-tool setup. Such a sequential inclusion of traditional multi-tool setups is reflected in the classification formula (1) by the operator $\boldsymbol{U_i}$ with index $\boldsymbol{i}$.

The filling of the classification formula (1) is provided by a system of codifiers. The codifier of installation methods can be taken from [35, 36], since the mounting on *CNC* machines is the same as on traditional cam-controlled lathes, for which the above classification was developed (Table 1).

Table 1

Codifier of workpiece mounting methods

No	Mounting method	Code k_y
1	In a chuck; in cantilever fashion	0
2	In a collet; in cantilever fashion	1
3	Between centers	2
4	In a chuck with a back center	3
5	Between centers with a steady rest	4

The carriage type codifier should be expanded to take into account the capabilities of modern *CNC* machines (Table 2).

Table 2

Carriage type codifier

No	Carriage type	Code k_c
1	Longitudinal	0
2	Cross feed	1
3	Top	2
4	Bottom	3
5	Rear	4
6	Pivoted	5
7	Compound	6
8	Turret	7

The cutting tool codifier is formed from the list of tools used on the entire group automatic lathes, both traditional (with cam control) and modern (with *CNC* and tool magazines) [38].

The feed type codifier for modern automatic lathes has a much more complex structure and does not fit into the framework of a simple coding table. Firstly, by its nature, feeds can be constant throughout the transition (parametric control) and variable (functional control). Feed variables are usually specified as a function of the tool path. Secondly, the feed direction has a decisive influence on the cutting force distribution pattern.

Basically, feeds are divided into longitudinal (along the axis of the workpiece) and transverse (along the normal to the axis of the workpiece). This was taken into account in the previous systematics [35, 36], by introducing feeds S_1 (longitudinal) and S_2 (transverse). However, on modern machines, the range of feeds is much wider. There are pivoted carriages, where the feed is carried out along the direction, oriented in different ways relative to the workpiece. For example, a pivoted carriage on vertical multi-spindle semi-automatic machines. When machining tapered surfaces, the carriage turns along the guide and feeds in this direction. Such a case can be described as a feed in the direction of a given vector e_s.

However, machining of the conical surface can be carried out in another way, by adding two coordinate feeds (longitudinal and transverse). This scheme works on most *CNC* machines. As a result, to describe the nature of the feed, it is proposed to use the feed code k_s. And in a special way to designate only the functional feed: $k_s = v$. If the feed is parametric, the feed type code in formula (1) is omitted.

The feed direction is given by the direction vector $\boldsymbol{e}_s$. For the convenience of reading the classification formula (1), it is proposed to introduce special notation for a number of special cases (typical) of the vector $\boldsymbol{e}_s$ (Table 3).

Table 3

Special type designations of feed direction vector

No	Direction of feed and method of its organization	Assignment of the vector $\boldsymbol{e}_s$
1	Feed along the ***x***-axis (longitudinal)	***x***
2	Feed along the ***y***-axis (transverse)	***y***
3	Feed along the ***z***-axis (tangential)	***z***
4	Feed in the ***xy*** plane, perpendicular to the ***z*** axis (carriage rotation)	***nz***
5	Feed in the ***xz*** plane, perpendicular to the ***y*** axis (carriage rotation)	***ny***
6	Feed in the ***yz*** plane, perpendicular to the ***x*** axis (carriage rotation)	***nx***
7	Feed in the direction specified by the vector in ***xyz*** space	$\boldsymbol{e}_s$

It should be noted that according to the *ISO 841–74* and *GOST 23597–79* standards, the information about the ***X***, ***Y***, ***Z*** axes presented in Table 3–11 for *CNC* machines should be interpreted as *X*⇒*Z*, *Y*⇒*X*, *Z*⇒*Y*. This is because, on *CNC* machines, the ***Z*** axis runs along the spindle axis, while the tool's transverse movement occurs along the ***X*** axis. Accordingly, the feeds are designated in this manner.

If the feed is formed by adding coordinate feeds, it is logical to describe it through the operation of combining these feeds. So, the machining of a cone by adding the longitudinal and transverse feeds will be described as: $\boldsymbol{S}(\boldsymbol{x})\cap\boldsymbol{S}(\boldsymbol{y})$.

As a vector $\boldsymbol{e}_c$, characterizing the location of the carriage, the radius vector of the point of the working surface of the carriage can be taken. Here it also makes sense to introduce a number of special type designations for this vector (Table 4).

Table 4

Special type designations of the carriage location vector

No	Carriage location	Carriage example	Assignment of the vector $\boldsymbol{e}_c$
1	***x***-axis carriage	Turret	***x***
2	***y***-axis carriage	Longitudinal on *ATL* and *HMAL*	***y***
3	***z***-axis carriage	Vertical on *ATL*	***z***
4	–***y***-axis carriage	Rear on *ATL*, carriage located on top of dual-carriage *CNC* machine	–***y***
5	Carriage located in the ***xy*** plane, perpendicular to the ***z*** axis	Carriage with rotation function on *VMSL*	***nz***
6	Carriage located in the ***yz*** plane, perpendicular to the ***y*** axis	Spindle with tools on a *CNC* machine	***ny***
7	Carriage located in the ***yz*** plane, perpendicular to the ***x*** axis	Transversal carriage on *HMAL*, spindle with tools on a *CNC* machine	***nx***
8	Carriage oriented in the direction specified by a vector in ***xyz*** space	Spindle with tools on a *CNC* machine	$\boldsymbol{e}_c$

When organizing multi-tool setups, it is not uncommon when, several tools are mounted on one carriage, individual tools are rotated relative to other tools due to the use of special holders. For example, two turning cutters are placed, rotated relative to each other by 180°.

To describe such a situation, the orientation vector of the cutting tool $\boldsymbol{e}_u$ is introduced in formula (1). Here, the vector $\boldsymbol{e}_u$ characterizes the direction of the axis of the cutting tool. By analogy with the vectors of the feed direction $\boldsymbol{e}_s$ and the location of the carriage $\boldsymbol{e}_c$, in this case it is also possible to introduce special designations for common typical situations (Table 5).

Table 5

Special type designations for the orientation vector of the cutting tool

No	Orientation of the cutting tool	Assignment of the vector $\boldsymbol{e}_u$
1	Along the $\boldsymbol{x}$-axis	$\boldsymbol{x}$
2	Along the $\boldsymbol{y}$-axis	$\boldsymbol{y}$
3	Along the $\boldsymbol{z}$-axis	$\boldsymbol{z}$
4	In the $\boldsymbol{xy}$ plane, perpendicular to the $\boldsymbol{z}$ axis	$\boldsymbol{nz}$
5	In the $\boldsymbol{xz}$ plane, perpendicular to the $\boldsymbol{y}$ axis	$\boldsymbol{ny}$
6	In the $\boldsymbol{yz}$ plane, perpendicular to the $\boldsymbol{x}$ axis	$\boldsymbol{nx}$
7	In any direction in $\boldsymbol{xyz}$ space	$\boldsymbol{e}_u$
8	Direction of the main component of cutting force from the cutting tool	Descending +; Downward –

Since the rotation of the cutting tool relative to the carriage is rarely used, it is proposed to describe the orientation of the tool only in cases where this rotation takes place. If the orientation of the tool coincides with the orientation of the working surfaces of the carriage, the element of the classification formula (1), which describes the orientation of the tool, is omitted.

The main goal of developing models of machining accuracy in multi-tool setups is to create effective algorithms for controlling the design process of these setups, assigning cutting conditions that ensure the required accuracy of all specified dimensions. The structure of control algorithms is largely determined by the type and number of control parameters. Since the spindle speed during multi-tool setup is the same for all setup tools, cutting speed is not a direct control factor. It can only be taken into account for each tool. The direct control factor is the tool feed, of course, taking into account the simultaneous operation of all setup tools.

On machines of the turning group, the feed is set for the carriage as a whole. Therefore, the number of carriages used in the setup already predetermines the number of given feeds, i.e. number of control factors. As a result, it is advisable to distinguish three main classes of multi-tool setups: single-carriage, double-carriage and multi-carriage.

As follows from the classification formula (1), on machines of the turning group, especially modern *CNC* machines, feeds are divided into single-coordinate and two-coordinate feeds according to the method of implementation. Single-coordinate feed is when the feed direction coincides with one of the coordinate axes of the workpiece being machined. A two-coordinate feed is formed by adding two feeds, each of which is carried out along its own coordinate. In this case, unlike the first one, we have two control factors (two coordinate feeds).

The main classes of the proposed systematics of multi-tool setups are considered bellow.

Results and Discussion

To create a matrix theory of multi-tool machining accuracy, a set of multi-tool setups was organized and classified. As a result, a formalized six-level classification is developed, which includes the following parameters: the method of workpiece mounting, the set of carriages, types of cutting tools, types and directions of carriage feeds, the orientation of tools relative to the workpiece, and the method of tool activation (either parallel or sequential). This classification takes into account the technological capabilities for organizing multi-tool machining for modern *CNC* lathes. The main classes of the developed systematization of multi-tool setups are single-carriage single-coordinate setups, single-carriage dual-coordinate setups, dual-carriage single-coordinate setups, dual-carriage dual-coordinate setups, and multi-carriage setups.

The developed classification of multi-tool setups on multi-carriage and multi-spindle *CNC* lathes allows for the creation of a matrix model of accuracy for each class, which will undoubtedly be structurally simpler, as well as a unified generalized model. Therefore, the classification discussed in this work is aimed at identifying the characteristics of force loading and deformation of the technological system during multi-tool machining.

The developed systematization of multi-tool setups on turning machines is oriented toward the development of machining accuracy models and can serve as a basis for creating recommendations for cutting conditions for these *CNC* machines. Using this approach, it is possible to systematically solve the problem of increasing efficiency in designing and developing recommendations on cutting modes for *CNC* machines. Since multi-tool machining involves numerous factors, its design inevitably requires the use of computer technologies. Therefore, the proposed classification of multi-tool setups can serve as a basis for developing the methodological support for *CAD* systems for new generation turning operations.

Based on the proposed classification, it is anticipated that a set of matrix models for machining accuracy will be developed in the future for single-carriage and dual-carriage multi-tool setups.

The main classes of the proposed systematization of multi-tool setups

Single-carriage single-coordinate setups. Single-carriage single-coordinate multi-tool setups based on a single carriage are used on various types of lathes with cam control. These include automatic turret lathes, horizontal automatic and semi-automatic multi-spindle lathes, vertical semi-automatic multi-spindle lathes, as well as automatic lathes for longitudinal profiling and shape-cutting automatic lathes. Such setups are also used on *CNC* machines. It can be implemented on carriages of any type (longitudinal, turret, or transverse). On turret lathes, both the upper and back carriages are considered transverse carriages.

The main feature of this class of multi-tool setups is that all tools are located on a single carriage, and there is only one control parameter: a specific coordinate feed.

Table 6 presents examples of typical setups from this class. The standard setups are labeled according to the proposed system (1).

For convenience of work, illustrated setups' guides have been developed as an appendix to each classifier (Table 7).

Single-carriage dual-coordinate setups. This type of setup is used on *CNC* lathes for machining conical and contoured surfaces. In these setups, the contour feed is formed by summing the coordinate feeds, such as longitudinal (along the $\boldsymbol{X}$ axis) and transverse (along the $\boldsymbol{Y}$ axis). When machining conical surfaces, the feed remains constant throughout the entire machining cycle, meaning that control is performed parametrically.

When machining profiled surfaces, the coordinate feeds are setup in accordance with the changes in the contour being machined, meaning the control is functional.

These differences are significant when developing control algorithms. It is essential for the accuracy model that it has two control factors.

Table 8 shows examples of applied setups of this class.

Dual-carriage single-coordinate setups. Multi-tool setups of this type are used on dual-carriage and multi-carriage lathes. These concerns traditional automatic and semi-automatic turning lathes with cam control, such as turret lathes, horizontal automatic and semi-automatic multi-spindle lathes, vertical semi-automatic multi-spindle lathes, as well as automatic lathes for longitudinal profiling and shape-cutting automatic lathes. These setups are often made on double-carriage *CNC* lathes.

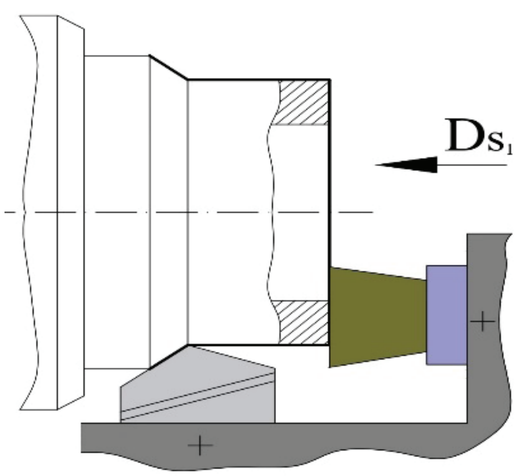
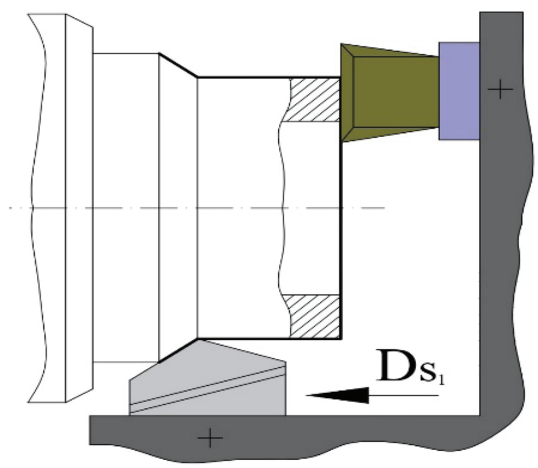
Table 6

Elements of the classifier of basic multi-tool single-carriage setups for a longitudinal carriage

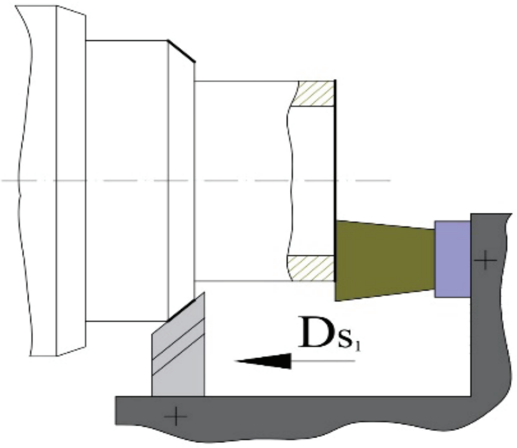
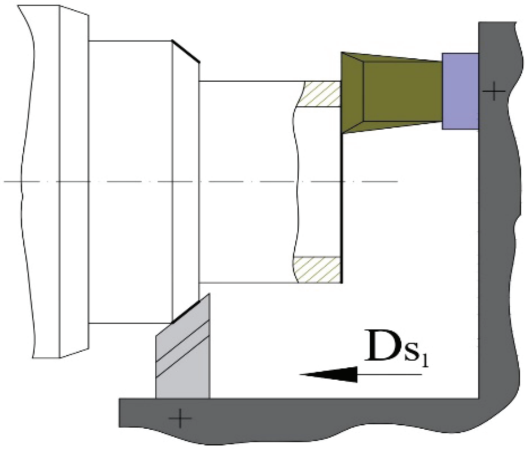
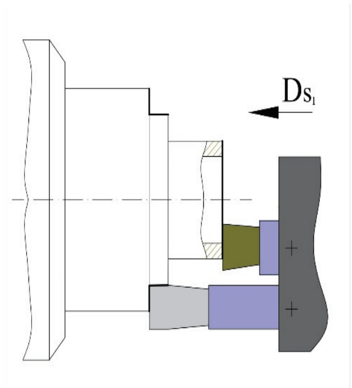
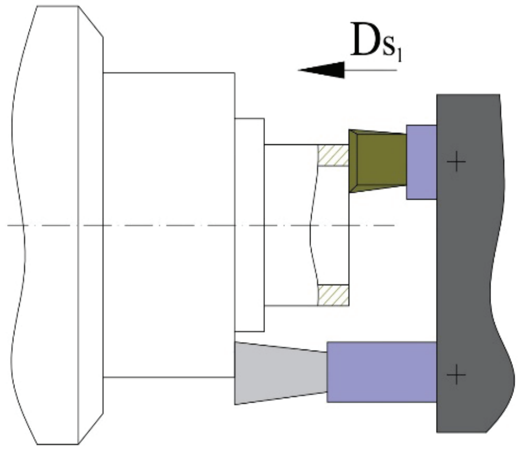
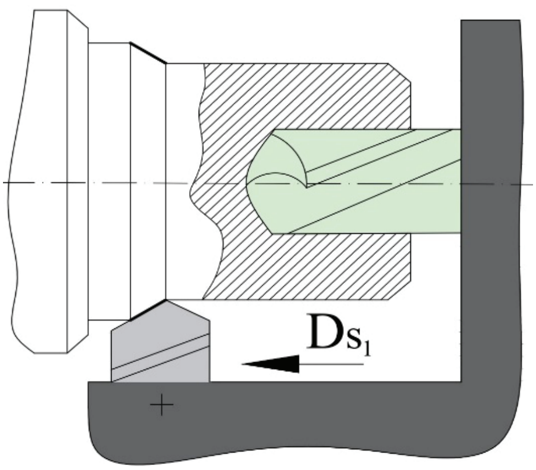
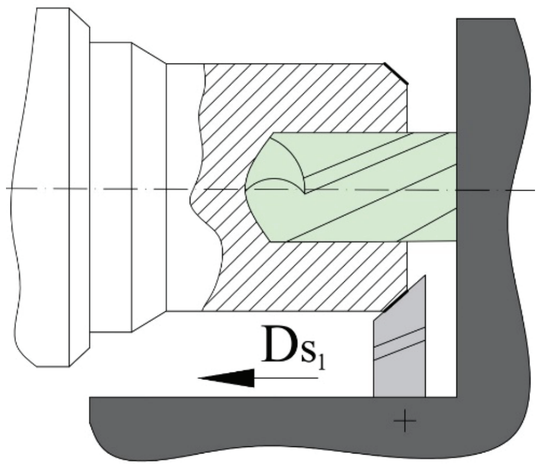
Tool		Turning cutter	Chamfering cutter
		1	2
Designation of adjustments			
Turning cutter	1	$Y0C0(y)S(x)[u_1 1(y) \cap u_2 1(y)]$ $Y0C0(y)S(x)[u_1 1(y) \cap u_2 1(-y)]$	
Chamfering cutter	2	$Y0C0(y)S(x)[u_1 2(y) \cap u_2 1(y)]$ $Y0C0(y)S(x)[u_1 2(y) \cap u_2 1(-y)]$	$Y0C0(y)S(x)[u_1 2(y) \cap u_2 2(y)]$ $Y0C0(y)S(x)[u_1 2(x) \cap u_2 2(x(-y))]$
…	…	…	…
Profile cutter	5	$Y0C0(y)S(x)[u_1 5(x) \cap u_2 1(y)]$ $Y0C0(y)S(x)[u_1 5(x) \cap u_2 1(-y)]$	$Y0C0(y)S(x)[u_1 5(x) \cap u_2 2(y)]$ $Y0C0(y)S(x)[u_1 5(x) \cap u_2 2(x(-y))]$
…	…	…	…
Drill	12	$Y0C0(y)S(x)[u_1 12(x) \cap u_2 1(y)]$ $Y0C0(y)S(x)[u_1 12(x) \cap u_2 1(-y)]$	$Y0C0(y)S(x)[u_1 12(x) \cap u_2 2(y)]$ $Y0C0(y)S(x)[u_1 12(x) \cap u_2 2(x(-y))]$
…	…	…	…

Table 7

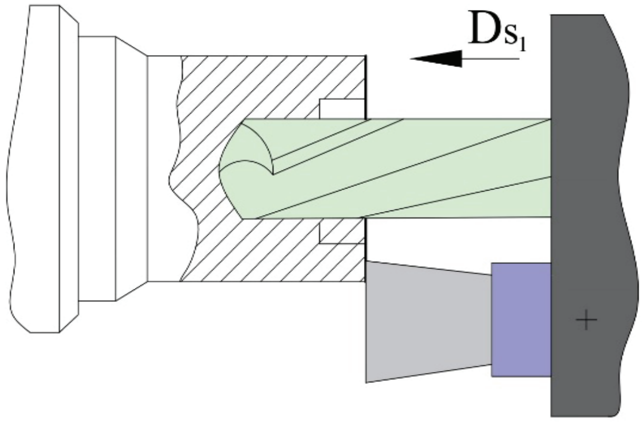
Fragments of the illustrated determinant. Elementary multi-tool setups on a longitudinal carriage (the part is mounted in the chuck)

Turning cutter	
$Y0C0(y)S(x)[u_1 4(x) \cap u_2 1(y)]$	$Y0C0(y)S(x)[u_1 4(x(-y)) \cap u_2 1(y)]$
	

Continuation of the Table 7

Chamfering cutter	
$Y0C0(y)S(x)\left[u_1 4(x)\cap u_2 2(y)\right]$	$Y0C0(y)S(x)\left[u_1 4(x(-y))\cap u_2 2(y)\right]$
	
Wide cutter	
$Y0C0(y)S(x)\left[u_1 4(x)\cap u_2 4(y)\right]$	$Y0C0(y)S(x)\left[u_1 4(x)\cap u_2 4(x(-y))\right]$
	
Drill	
$Y0C0(y)S(x)\left[u_1 12(x)\cap u_2 1(y)\right]$	$Y0C0(y)S(x)\left[u_1 12(x)\cap u_2 2(y)\right]$
	

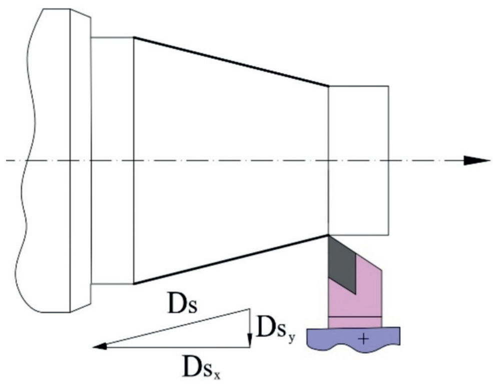
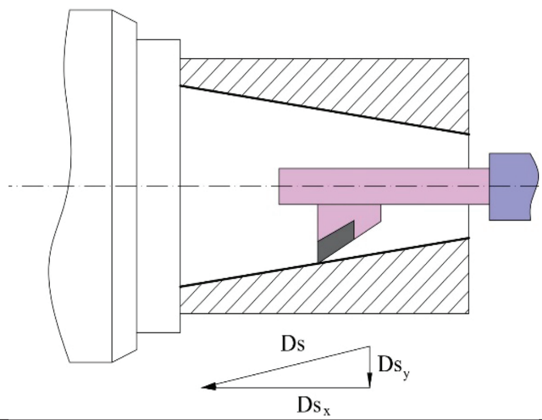
The End Table 7

$Y0C0(y)S(x)[u_1 12(x) \cap u_2 4(y)]$


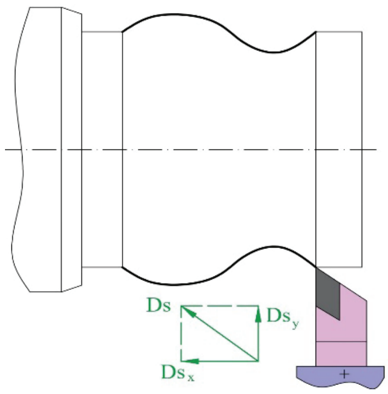
Note: Recommended setups are highlighted in **red**, while possible but not recommended setups are shown in **black**.

Table 8

Examples of single-carriage two-coordinate setups

Setup name	Tool	Setup layout
Machining an external cone with a single tool using feeds along the coordinate axes $\boldsymbol{x}$ and $\boldsymbol{y}$: $\boldsymbol{S_x}$ and $\boldsymbol{S_y}$	Cutting tools for straight turning on *CNC* machines	$Y0C0(y)S(x)[u17(y)]$ 
Machining an internal cone with a single tool using feeds along the coordinate $\boldsymbol{x}$ and $\boldsymbol{y}$: $\boldsymbol{S_x}$ and $\boldsymbol{S_y}$	Cutting tools for boring on *CNC* machines	$Y0C0(y)S(x)[u19(y)]$ 

The End Table 8

Setup name	Tool	Setup layout
Single tool external profile turning with two feeds S_x and S_y	Cutters for *CNC* machines, contour turning	$Y0C0(y)S(x)[u18(y)]$ 

A characteristic feature of two-carriage single-coordinate setups is the presence of two control parameters – the feed of each carriage. However, these parameters are not equal. The feed of the carriage on which the tool that forms the considered dimension is mounted is a direct, immediate control factor. The supply of another carriage, the tools of which form other dimensions, has only an indirect effect on the accuracy of the considered dimension.

Table 9 shows examples of applied multi-tool setups of this class.

Table 10 shows examples of possible and applicable setups of this class.

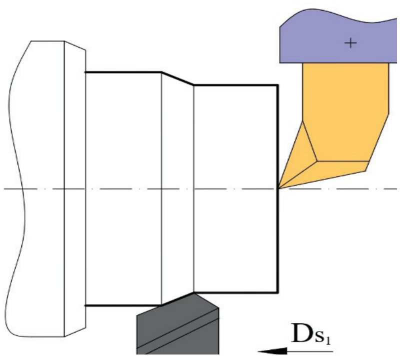
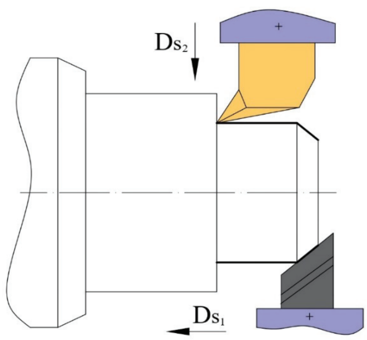
Dual-carriage dual-coordinate setups. These setups can be implemented on modern dual-carriage *CNC* lathes. In general, machining on each carriage can be controlled by two coordinate feeds. However, even the presence of such control on only one carriage, along with a second carriage in the setup, categorizes the setups into this class.

Multi-carriage setups. Setups of this class can be carried out on traditional cam-controlled machines: automatic turret lathes and automatic longitudinal profile turning. It is possible to implement such setups on modern double-carriage *CNC* machines, if an additional tool spindle with an independent drive is used.

Table 11 shows examples of possible and applicable setups of this class.

Table 9

Examples of elementary two-carriage one-coordinate setups (the part is mounted in the chuck)

The tool mounted on the transverse carriage	The tool mounted on the longitudinal carriage	
	Cutting tool for straight turning	Cutting tool for chamfering
Cutting tool for facing surfaces		
	$Y0C_1 0(y)S_1(x)[u1(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u9(-y)]$	$Y0C_1 0(y)S_1(x)[u2(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u9(-y)]$

The End Table 9

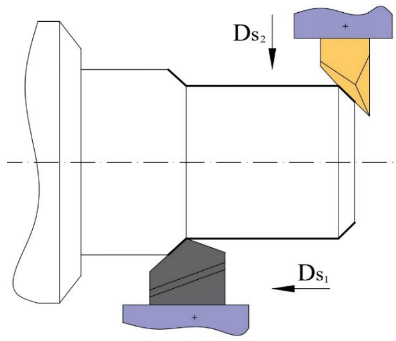
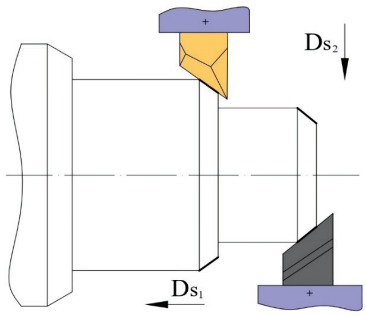
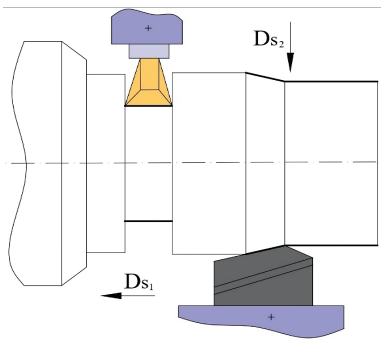
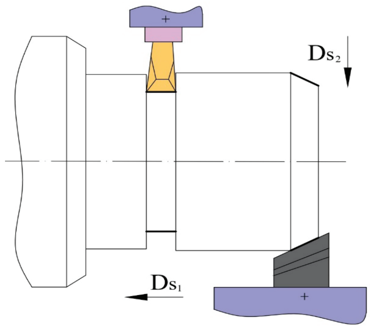
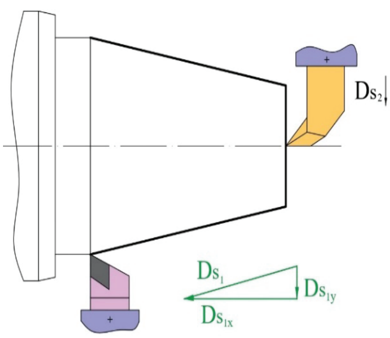
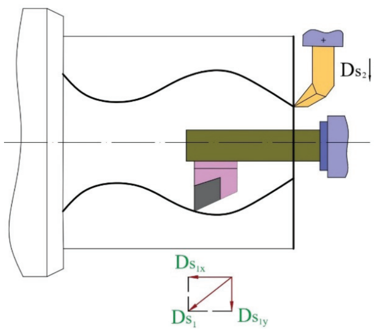
The tool mounted on the transverse carriage	The tool mounted on the longitudinal carriage	
	Cutting tool for straight turning	Cutting tool for chamfering
Chamfering cutter		
	$Y0C_1 0(y)S_1(x)[u1(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u2(-y)]$	$Y0C_1 0(y)S_1(x)[u2(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u2(-y)]$
Groove cutter		
	$Y0C_1 0(y)S_1(x)[u1(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)\left[u3\left(-y(-x)\right)\right]$	$Y0C_1 0(y)S_1(x)[u2(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)\left[u3\left(-y(-x)\right)\right]$

Table 10

Possible and applicable variants of two-carriage two-coordinate setups

Tool mounted on the transverse carriage	Tool mounted on the longitudinal carriage	
	Straight turning tools used on *CNC* machines	Turning tools for boring surfaces on *CNC* machines, used for machining contoured surfaces
Cutter for facing operation		
	$Y0C_1 0(y)S_1(x)[u17(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u9(-y)]$	$Y0C_1 0(y)S_1(x)[u18(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u9(y)]$

The End Table 10

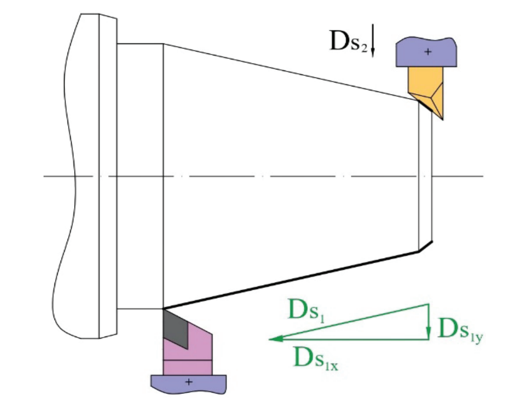
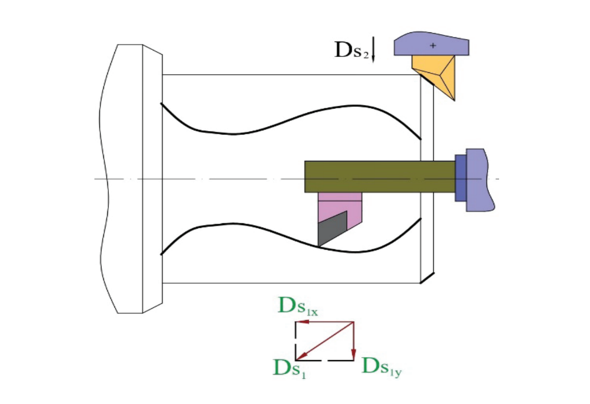
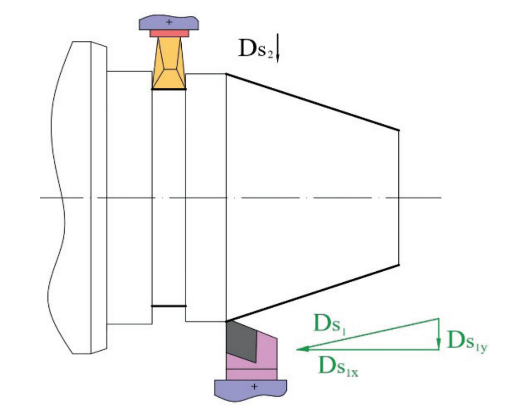
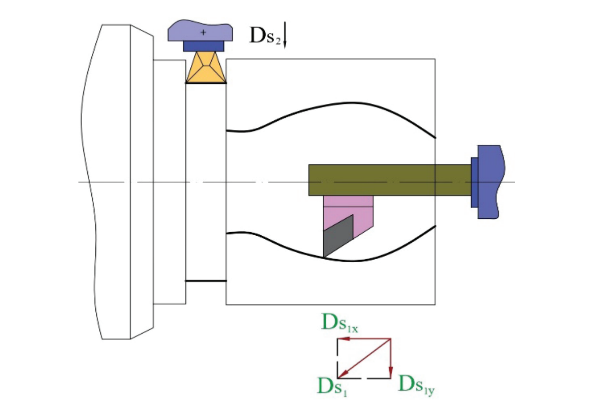
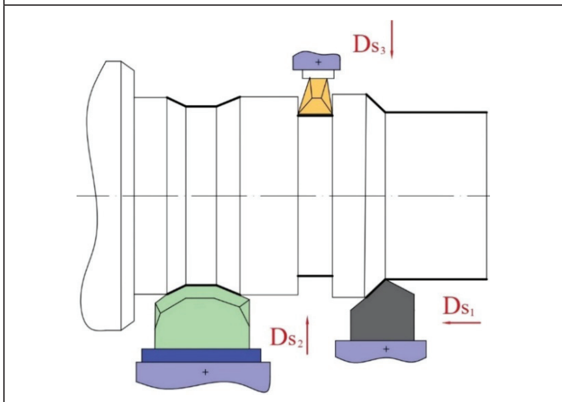
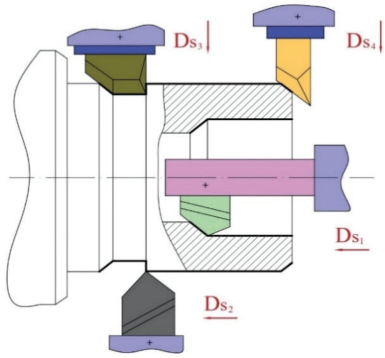
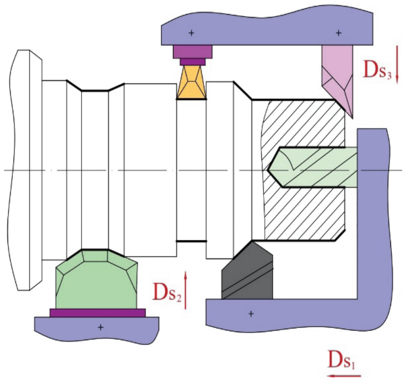
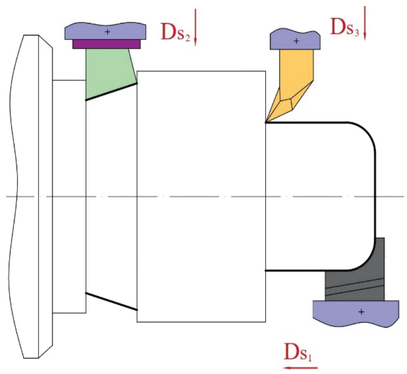
Tool mounted on the transverse carriage	Tool mounted on the longitudinal carriage	
	Straight turning tools used on *CNC* machines	Turning tools for boring surfaces on *CNC* machines, used for machining contoured surfaces
Chamfering cutter		
	$Y0C_1 0(y)S_1(x)[u17(y)] \cup$ k $\cup Y0C_2 1(y)S_2(y)[u2(-y)]$	$Y0C_1 0(y)S_1(x)[u18(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u2(y)]$
Groove cutter		
	$Y0C_1 0(y)S_1(x)[u17(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u3(-y(-x))]$	$Y0C_1 0(y)S_1(x)[u18(y)] \cup$ $\cup Y0C_2 1(y)S_2(y)[u3(y(-x))]$

Table 11

Examples of multi-carriage setups

Setups layout	Designation
	$Y0C_1 7(x)S_1(x)[u1(y)] \cup Y0C_2 1(y)S_2(y)(y)[u3(-y(-x))] \cup$ $\cup Y0C_3 2(y)(y)S_3(y)[u5(y)]$

The End Table 11

Setups layout	Designation
	$Y0C_1 7(x)S_1(x)\left[u7(y)\right] \cup Y0C_2 0(y)S_2(x)\left[u1(-y)\right] \cup$ $Y0C_3 1(y)S_3(y)[u5(y)] \cup Y0C_4 3(z)S_4(y)[u2(y)]$
	$Y0C_1 7(x)S_1(x)[u_1 12(x) \cap u_2 1(y)] \cup Y0C_2 2(z)S_2(y)[u5(y)] \cup$ $\cup Y0C_3 1(y)S_3(y)[u_1 3(-y) \cap u_2 2(-y)]$
	$Y0C_1 7(x)S_1(x)[u5(y)] \cup Y0C_2 1(y)S_2(y)\left[u4(-y(-x))\right] \cup$ $\cup Y0C_3 2(z)S_3(y)[u9(-y)]$

Conclusions

1. A new, multi-factorial systematics of multi-tool setups is developed, taking into account the rich technological possibilities for organizing multi-tool machining for modern *CNC* machines.

2. A classification of multi-tool setups is carried out with the identification of the applicability of types of setups and the formation of setup classes that have a common mechanism for the formation of an error. The creation of effective algorithms for managing the process of designing these setups is substantiated.

3. The proposed systematization of multi-tool setups on lathes is intended for creating a matrix model of machining accuracy. The main feature of multi-tool machining lies in the force interaction between the tools in the setup. Therefore, the classification of multi-tool setups aims to identify the characteristics of force loading and deformation of the technological system during such machining. This can serve as a basis for developing cutting condition recommendations for *CNC* machines.

4. The developed classification of multi-tool setups forms the basis of methodological support for *CAD* systems for lathe-automatic operations and serves as the basis for creating *CAD* systems for new generation turning operations.

References

1. Shinno H., Hashizume H. Structured method for identifying success factors in new product development of machine tools. *CIRP Annals – Manufacturing Technology*, 2002, vol. 51 (1), pp. 281–284. DOI: 10.1016/S0007-8506(07)61517-0.

2. Moriwaki T. Multi-function machine tool. *CIRP Annals – Manufacturing Technology*, 2008, vol. 57 (2), pp. 736–749. DOI: 10.1016/j.cirp.2008.09.004.

3. Brecher C., Esser M., Witt S. Interaction of manufacturing process and machine tool. *CIRP Annals – Manufacturing Technology*, 2009, vol. 58 (2), pp. 588–607. DOI: 10.1016/j.cirp.2009.09.005.

4. Tomiyama T., Gu P., Jin Y., Lutters D., Kind Ch., Kimura F. Design methodologies: industrial and educational applications. *CIRP Annals – Manufacturing Technology*, 2009, vol. 58 (2), pp. 543–565. DOI: 10.1016/j.cirp.2009.09.003.

5. Shinno H., Yoshioka H., Sawano H. A frame-work for systematizing machine tool engineering. *International Journal of Automation Technology*, 2013, vol. 7 (6), pp. 760–768. DOI: 10.20965/ijat.2013.p0760.

6. Usubamatov R., Harun A., Sanuddin A. Optimisation of machining parameters by criterion of maximum productivity. *International Journal of Production Research*, 2014, vol. 52 (10), pp. 2946–2953. DOI: 10.1080/00207543.2013.857440.

7. Usubamatov R., Zain Z., Sin T. Optimization of multi-tool machining processes with simultaneous action. *International Journal of Advanced and Manufacturing Technology*, 2016, vol. 82, pp. 1227–1239. DOI: 10.1007/s00170-015-6920-x.

8. Levin G., Rozin B., Dolgui A. Optimization of multi-tool cutting modes in multi-item batch manufacturing system. *IFAC Proceedings Volumes*, 2013, vol. 46 (9), pp. 766–771. DOI: 10.3182/20130619-3-RU-3018.00357.

9. Cakir M.C., Gurarda A. Optimization of machining conditions for multi-tool milling operations. *International Journal of Production Research*, 2000, vol. 38 (15), pp. 3537–3552. DOI: 10.1080/002075400422789.

10. Dolgui A., Levin G., Rozin B. Optimisation of the aggregation and execution rates for intersecting operation sets: an example of machining process design. *International Journal of Production Research*, 2000, vol. 58 (9), pp. 2658–2676. DOI: 10.1080/00207543.2019.1629668.

11. Daoud Z., Purcheck G. Multi-tool job sequencing for tool-change reduction. *International Journal of Production Research*, 1981, vol. 19 (4), pp. 425–435. DOI: 10.1080/00207548108956670.

12. Torres W., Brand M., Serebrenik A. A systematic literature review of cross-domain model consistency checking by model management tools. *Software and Systems Modeling*, 2021, vol. 20 (3), pp. 897–916. DOI: 10.1109/SYSCON.2017.7934729.

13. Yusubov N., Abbasova H. Models for machining accuracy in multi-tool adjustment. *International Journal of Automotive and Mechanical Engineering*, 2020, vol. 17 (3), pp. 8067–8085. DOI: 10.15282/ijame.17.3.2020.01.0605.

14. Kalidasan R., Senthilvelan S., Dixit U.S., Vaibhav J. Double tool turning: machining accuracy, cutting tool wear and chip morphology. *International Journal of Precision Technology*, 2016, vol. 6 (2), p. 142. DOI: 10.1504/IJPTECH.2016.078189.

15. Brecher C., Epple A., Neues S., Fey M. Optimal process parameters for parallel turning operations on shared cutting surfaces. *International Journal of Machine Tools and Manufacture*, 2015, vol. 95, pp. 13–19. DOI: 10.1016/j.ijmachtools.2015.05.003.

16. Fu R., Curley P., Higgins C., Kilic Z., Sun D., Murphy A., Jin Y. Double-sided milling of thin-walled parts by dual collaborative parallel kinematic machines. *Journal of Materials Processing Technology*, 2022, vol. 299, p. 117395. DOI: 10.1016/j.jmatprotec.2021.117395.

17. Zhao X., Tao B., Yang L., Ding H. Asymmetrical nonlinear impedance control for dual robotic machining of thin-walled workpieces. *Robotics and Computer-Integrated Manufacturing*, 2020, vol. 63, p. 101889. DOI: 10.1016/j.rcim.2019.101889.

18. Yan Y., Xu J., Wiercigroch M. Stability and dynamics of parallel plunge grinding. *International Journal of Advanced and Manufacturing Technology*, 2018, vol. 99, pp. 881–895. DOI: 10.1007/s00170-018-2440-9.

19. Yamato S., Nakanishi K., Suzuki N. Development of automatic chatter suppression system in parallel milling by real-time spindle speed control with observer-based chatter monitoring. *International Journal of Precision Engineering and Manufacturing*, 2021, vol. 22, pp. 227–240. DOI: 10.1007/s12541-021-00469-2.

20. Weck M., Staimer D. Parallel kinematic machine tools – current state and future potentials. *CIRP Annals – Manufacturing Technology*, 2002, vol. 51 (2), pp. 671–683. DOI: 10.1016/S0007-8506(07)61706-5.

21. Azvar M., Budak E. Multi-dimensional chatter stability for enhanced productivity in different parallel turning strategies. *International Journal of Machine Tools and Manufacture*, 2017, vol. 123, pp. 116–128. DOI: 10.1016/j.ijmachtools.2017.08.005.

22. Kanakaraju V., Hassan F., Kalidasan R. Numerical analysis of surface integrity in parallel turning. Part A: Influence of cutting tool nose radius. *Materials Today: Proceedings*, 2021, vol. 38 (1), pp. 186–190. DOI: 10.1016/j.matpr.2020.06.511.

23. Hassan F., Kanakaraju V., Kalidasan R., Norkey G. Numerical analysis of surface integrity in parallel turning. Part B: Influence of cutting tool chamfer angle and chamfer width. *Materials Today: Proceeding*s, 2021, vol. 44 (1), pp. 266–270. DOI: 10.1016/j.matpr.2020.09.464.

24. Brecher C., Trofimov Y., Bäumler S. Holistic modelling of process machine interactions in parallel milling. *CIRP Annals – Manufacturing Technology*, 2011, vol. 60 (1), pp. 387–390. DOI: 10.1016/j.cirp.2011.03.025.

25. Yusubov N.D., Abbasova H.M., Khankishiyev İ.A. Entwicklung einer projektierungstheorie für die mehrwerkzeugbearbeitung mit den möglichkeiten der modernen CNC-werkzeugmaschinen. *Forschung im Ingenieurwesen*, 2021, vol. 85, pp. 661–678. DOI: 10.1007/s10010-021-00478-7.

26. Yusubov N.D. Matrix models of the accuracy in multitool two-support setup. *Russian Engineering Research*, 2009, vol. 29, pp. 268–271. DOI: 10.3103/S1068798X09030125.

27. Bogatenkov S.A., Sazonova N.S., Yusubov N.D., Mammadov P.V., Bazhenov R.I. Increasing the productivity of multitool machining on automated lathes by optimizing the machining plan. *Russian Engineering Research*, 2021, vol. 41 (11), pp. 1071–1074. DOI: 10.3103/S1068798X21110046.

28. Bogatenkov S.A., Sazonova N.S., Guzeev V.I., Yusubov N.D., Abbasova G.M. Increasing the productivity of multitool machining on automated lathes by optimizing the tool positions. *Russian Engineering Research*, 2021, vol. 41 (11), pp. 1075–1079. DOI: 10.3103/S1068798X21110058.

29. Usher J.M., Bowden R.O. The application of genetic algorithms to operation sequencing for use in computer-aided process planning. *Computers & Industrial Engineering*, 1996, vol. 30 (4), pp. 999–1013. DOI: 10.1016/0360-8352(96)00048-4.

30. Indrajit M., Pradip K.R. A review of optimization techniques in metal cutting processes. *Computers & Industrial Engineering*, 2006, vol. 50 (1–2), pp. 15–34. DOI: 10.1016/j.cie.2005.10.001.

31. Usubamatov R., Ismail K.A., Sah J.M. Mathematical models for productivity and availability of automated lines. *The International Journal of Advanced Manufacturing Technology*, 2013, vol. 66, pp. 59–69. DOI: 10.1007/s00170-012-4305-y.

32. Ozturk E., Comak A., Budak E. Tuning of tool dynamics for increased stability of parallel (simultaneous) turning processes. *Journal of Sound and Vibration*, 2016, vol. 360, pp. 17–30. DOI: 10.1016/j.jsv.2015.09.009.

33. Yusubov N., Abbasova H. Full-factor matrix model of accuracy of dimensions performed on multi-purpose CNC machines. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23 (4), pp. 6–20. DOI: 10.17212/1994-6309-2021-23.4-6-20.

34. Kurt A., Sürücüler S., Kirik A. Developing a mathematical model for the cutting forces prediction depending on the cutting parameters. *Technology*, 2010, vol. 13 (1), pp. 23–30.

35. Koshin A.A. *Teoriya tochnosti i optimizatsiya mnogoinstrumentnoi tokarnoi obrabotki*. Diss. dokt. tekhn. nauk [Accuracy theory and optimization of multi-tool turning. Dr. eng. sci. diss.]. Chelyabinsk, 1997. 290 p. (In Russian).

36. Koshin A.A. *Obrabotka na tokarnykh stankakh: naladka, rezhimy rezaniya* [Processing on lathes: adjustment, cutting conditions]. Handbook. Chelyabinsk, Siti-Print Publ., 2012. 744 p.

37. Koshin A.A., Yusubov N.D. Elementy matrichnoi teorii tochnosti mnogoinstrumentnoi obrabotki v prostranstvennykh naladkakh [Elements of matrix theory of multitool processing accuracy in three-dimensional setups]. *Vestnik mashinostroeniya = Russian Engineering Research*, 2013, no. 9, pp. 13–17. (In Russian).

38. Yusubov N.D., Abbasova Kh.M., Dadashov R.E. [Models of cutting forces during mechanical machining on modern machines of turning group]. *Vserossiiskii forum molodykh issledovatelei – 2023* [All-Russian forum of young researchers – 2023]. Petrozavodsk, 2023, pp. 236–246. (In Russian).

Conflicts of Interest

The authors declare no conflict of interest.