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machine tool, development,
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DEVELOPMENT OF HIGH PERFORMANCE MACHINE TOOLS

This paper presents a general characteristic of modern cutting machine tools and their role in achieving high machining performance. The determinants of machine tool development, stemming from the constant development of products and their complexity and from market demands, are discussed in detail. Special attention is devoted to the improvement of the machine tool structure and its variations created in response to the continuous and flexible increase in machining efficiency. The importance of developing multitask, hybrid and reconfigurable structures is discussed. The essence of the development of multi-spindle units as the modules having a decisive influence on machining performance, precision and costs is described. Moreover, trends in the development of feed units and distance measuring systems are presented.

1. INTRODUCTION

Historically, machine tool tasks first came down to the generation of a specified trajectory of tool motion relative to the workpiece, and proper forces and torques needed to overcome cutting resistance. Then motion and workpiece precision began to be required, which led to the precise identification of motion disturbances and to precision machining, diagnosing and supervision. This became possible thanks to the development of open CNC systems. As attention focused on machined part precision, all precision disturbances originating from each machine tool part, including the production jig and process and the production/machining environment, had to be comprehensively considered. Such a holistic approach (the only one proper) requires the use of modelling and simulation of the whole autonomous machine tool module.

Cutting machine tools are the main components of contemporary manufacturing systems. Their operating parameters, purchase and operating costs and lifetime greatly affect the quality of the products and their production costs and delivery-to-market time. In recent years machine tools are increasingly often required to machine products complicated in shape, the batches become smaller and single products must be machined economically and quickly (preferably as ready-made). At the same time new difficult to machine high-strength construction materials and materials requiring very high cutting speeds appear. In

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order to meet these demands particular emphasis is placed on the proper development of machine tool modules and whole machine tools. The aim of their improvement is to increase broadly understood manufacturing/machining performance in order to increase the competitiveness of the products. Moreover, machine tools (and in the wider context, the whole machine-tool industry) are of strategic importance to the technological potential of each country in which highly sophisticated products are created and manufactured.

Machine tools are production machines whose mechanical, mechatronic and software components are highly complex. Since the requirements as to the speed and quality of the processes to be carried out by machine tools are very high, state-of-the-art technologies and techniques are employed to build and effectively operate them. As advances in materials engineering are made, new mechanical and mechatronic components are incorporated. As a result, machine tools can withstand greater static and dynamic loads and become smaller while the operating resistances and power losses decrease. The incorporated mechatronic elements significantly improve machine tools' operational properties and their adjustment. Thanks to this, machine tool components and whole machine tools can operate intelligently by adapting their functions to the performed tasks.

In order to achieve the highest possible performance and product quality, attempts are made to boost (through innovation) the development of machine tools. A high performance/quality synergy can be achieved through the implementation of an innovative concept of all the major machine tool modules. This particularly applies to controllable axis modules, tool modules, CNC modules, system and technological software modules, the combining of highly organized technological tooling systems for high-precision products and the combining of many machining methods for multitasking, hybridity and prospective intelligent self-control. In order to explain the problems involved in the creation of innovative machine tool modules and in the improvement of the latter and of the whole machine tool structures, the general determinants of their development and the determinants specific for selected major modules are presented below.

2. DETERMINANTS OF MACHINE TOOLS DEVELOPMENT

A contemporary cutting machine tool is a very complex product created to satisfy the demands of the local and global market and, in general, to meet the needs of the production systems. The market demands machine tools with operating parameters ensuring highly efficient manufacturing and competitively low production costs. The products need to be inexpensive and have good service properties and long lifetime. The machine tool as a component of a manufacturing system must meet the production cost-effectiveness and quality requirements of each factory manufacturing environment. It is the best when themachine tool can be easily adapted to each manufacturing system and environment and when its technological capacity is large. From the global point of view, when creating a machine tool one should take into account that:

- the products which it will manufacture will have different liftetimes determined by complex conditions,

- the lifetime of products constantly changes,
- strategies of delivering products to market change,
- products need to be flexible, fulfilling increasingly more functions/customer requirements, including environmental requirements (green products).

As regards the manufacturing system needs, the machine tool should offer:

- manufacturing technology sophistication making it possible to achieve high product operating accuracy,
- a large technological capacity making it possible to carry out all machining (even hybrid machining),
- very fast realization of processes,
- high adaptability to technological tasks and if necessary, also structure reconfigurability,
- high dimensional accuracy and high surface layer quality,
- maximum process environmental friendliness (which includes the lowest possible energy consumption),
- high service and maintenance friendliness,
- optimal fittability in the real and virtual model of a fast-changing plant thanks to manufacturing system and module self-organizability and self-adjustment [1].

The contemporary highly productive machine tool with a high technological capacity must carry out very complex tasks, employing the simplest mechanical and mechatronic modules and very complex and efficient software modules. The machine tool must be extremely flexible – easily adaptable to tasks and changes in the operational parameters. The high adaptability of mechanical and mechatronic modules requires robust and efficient interfaces/connections which do not introduce mutual position errors when modules are added, or disturb the transmission of data. Because of the high machining precision and speed, precise and highly organized mechatronic systems/modules, based on precise sensors and actuators, regulators and controllers and a very efficient communication system, need to be employed. In many cases, the sensors, the actuators and the signal processing systems must be miniature and remotely supplied and controlled with utmost precision.

Considering that a jump in performance can be achieved through innovation, the machine tool operation concept should be open to changes in both hardware and software, allowing one to incorporate innovative processes and make the necessary structural changes [2]. Such openness significantly increases the machine tool's lifetime and competitiveness and facilitates its improvement.

Therefore it is necessary to view the machine tool as a mechatronic system with constantly increasing task complexity and requiring the continuous application of the state-of-the-art electrical, electronic and software solutions. Consequently, the design of the machine tool load-bearing structure (which must have proper static, thermal and dynamic properties) becomes complicated. For this purpose one must have not only extensive theoretical and practical knowledge and dedicated computing systems, but also the capability to accurately experimentally test prototypes and to fine-tune computing models [3].

Machine tools form the lowest (but basic) manufacturing level which determines the performance and the production costs and is key for manufacturing, marketing and plant development. Thus it is important what measures of performance are used. In the literature on the subject one can find many such measures. From the historical perspective the measures are presented in Fig. 1 [4]. It appears from this figure that currently performance is evaluated using several criteria based on the factors which, according to current knowledge, determine it. High performance is the resultant of complex interactions of technological factors, to a large extent dependent on the well organized motivation of the workers responsible for its development. The criteria also include flexibility, although it is not directly mentioned because of the lack of a proper indicator.

A major criterion for improving a machine tool is an increase in its lifetime. An important indicator for improvement is the significance and frequency of (e.g. assembly) errors recorded by the service personnel. According to [5], faults most frequently occur in axle drives – 38%, spindle units and tool changers – 26% and in the electronics – 23%. In order to reduce the number of machine tool errors, machine tool complexity must be reduced. Complexity reduction leads to higher reliability, easier synchronization of repairs, more accurate prediction of machine tool behaviour, needed for rational improvements and effective error compensation. The result is increased performance.

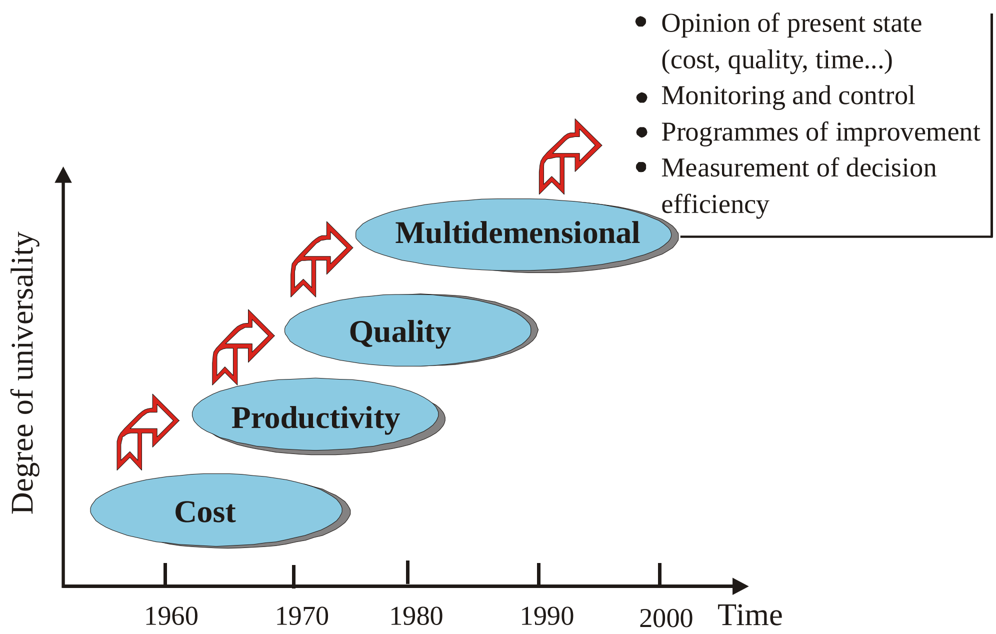


Fig. 1. Evolution of performance measures [4]

When considering accuracy as the criterion of high performance one should note the great advances made in manufacturing precision (Fig. 2) [6]. The requirements as to machining precision are currently very high. In the case of highly productive machine tools, high dimensional accuracy (in the order of 1µm) of the machined workpieces, and surface finish Ra < 0.1-0.2 µm can be achieved, but only by the leading machine tool producers. Most effort aimed at increasing performance goes into highly automated medium size machine tools, such as turning and milling centres and to a lesser extent, grinding centres.

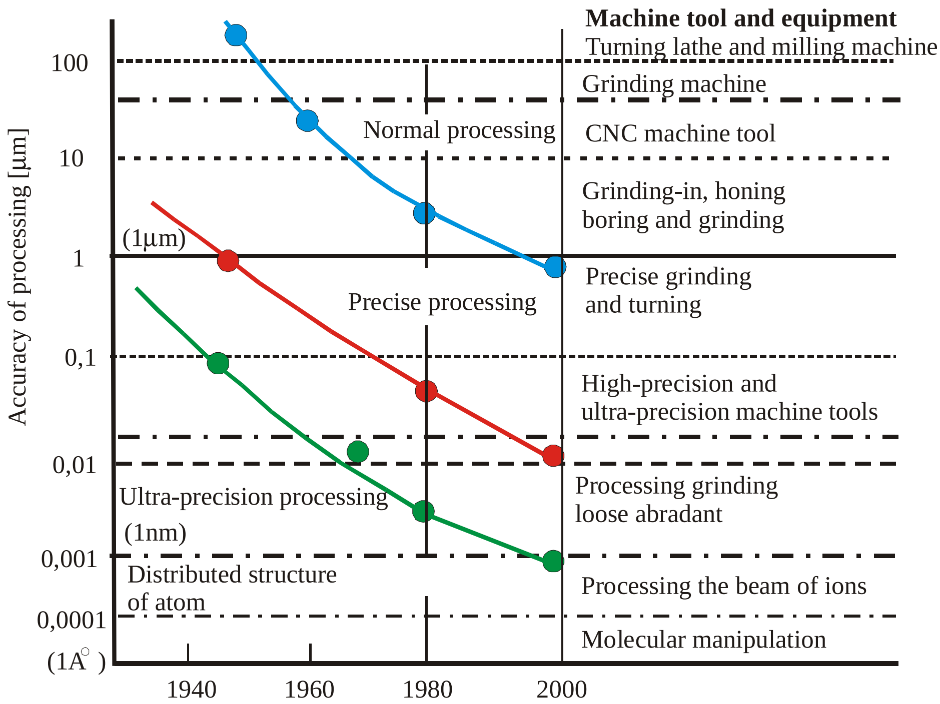


Fig. 2. Development of machining accuracy [6]

As the demand for the machining of small and very small elements grows, the micromachine tools used for this purpose must be very productive. Ultra-precision machine tools are employed to machine the very complicated shapes of the optical lenses used in, e.g., digital cameras and mobile phones, and microelectronic components made of hard-to-machine materials such as tungsten carbide and ceramics. For this purpose very high spindle and feeding speeds and very precise (simultaneous) control (particularly of thermal displacements which greatly affect machining precision) are needed.

Large machine tools also can be highly productive, but their flexibility (reconfigurability) is significantly limited by the very heavy weight of the individual mechanical and mechatronic modules.

Machine tool self-adjustment can ensure the highest level of performance. A self-organizing machine tool system is the optimal (future) solution. It has biological features and combines many very useful properties [7], such as:

- autonomy – operation according to self-generated rules and strategies,
- perception – interpreting a strategy and responding to local conditions and environment,
- learning – acquisition of new knowledge,
- naturalness,
- coaction.

In order to manufacture and improve self-organizing machine tools, cutting-edge mechatronic, mechanical and software solutions need to be employed. This particularly applies to rotary and linear axles effecting the necessary very high rotational and feeding speeds and so determining the performance (Fig. 3).

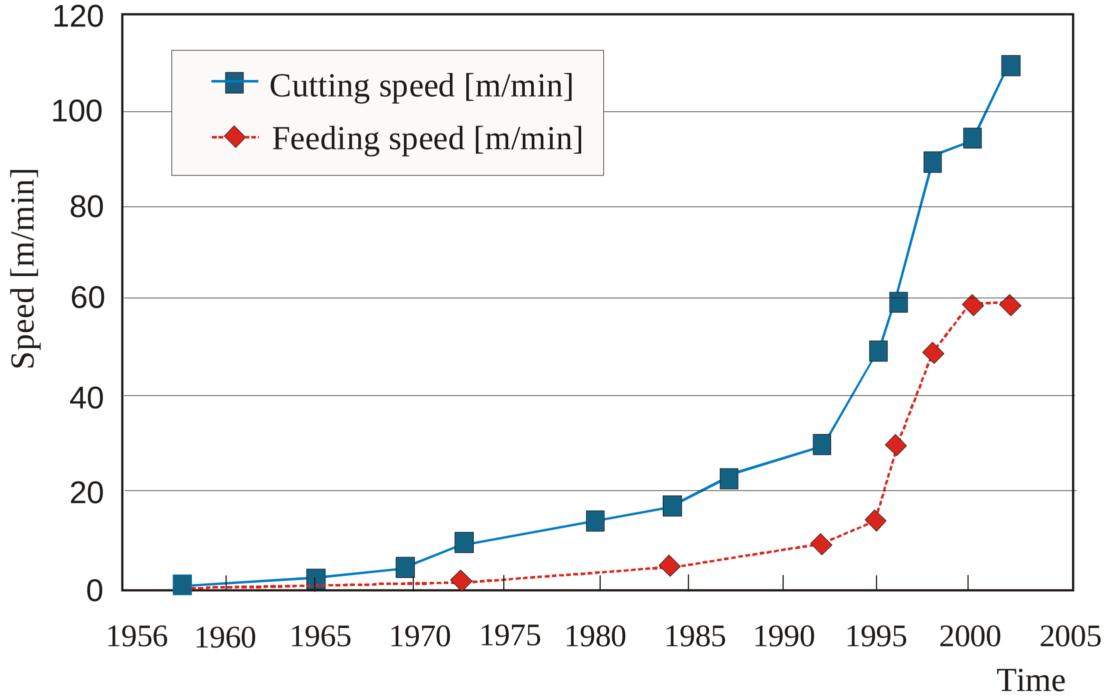


Fig. 3. Progress in feed rate for machining centre [26]

The determinants of the development of machine tools (particularly the highly productive ones) clearly show that extensive and most current knowledge is needed for their further development. This means that the design and operation of advanced machine tools must be based on very deep knowledge. Therefore the tasks involved in creating highly productive machine tools often must be divided among research centres and companies which have the indispensable knowledge and continuously broaden it.

3. IMPROVEMENT OF MACHINE TOOL STRUCTURE

The marked tendency to machine (as ready-made) ever smaller batches and even single workpieces, by means of a single machine tool spurred the development of modules and whole machine tools which make this possible. It became necessary to combine many diverse processes such as: machining, abrasive machining, forming, thermal treatment, electrolytic machining, laser machining, object manipulation and performing measurements on the machine tool.

Current machine tools have a modular structure, whereby their mechanical and mechatronic modules (made by both the machine tool producer and specialized firms keenly interested in their continuous development and modernization) can be independently improved. The innovative development of such modules greatly improves their operating parameters and contributes to a large increase in the efficiency of the machine tool. At the same time, it is observed that the effectiveness of each technology decreases over time as the technology ages (Fig. 4) [8].

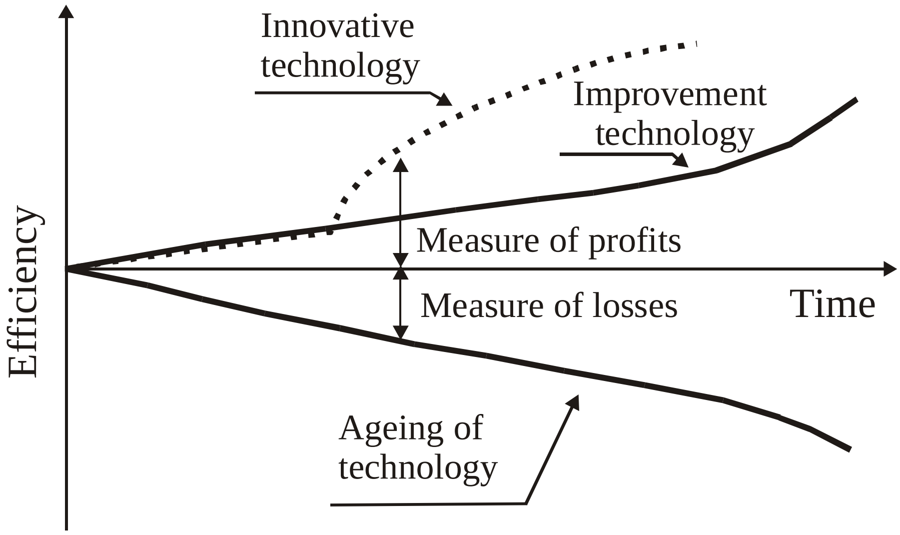


Fig. 4. Technology/machine tool performance change in time [8]

The lifetime of a machine tool module depends on the innovation weight which usually derives from the application of a new model operation concept and the use of novel materials improving the module’s static, dynamic and thermal properties and its wear resistance. In many cases a big improvement in module operating parameters is achieved through the incorporation of active mechatronic systems. Thanks to this solution the service parameters of modules can be adjusted (calibrated) to the operating requirements (Fig. 5). In this way one can influence the force, the torque, the tension (of, for example, the bearings), deformations, displacements, vibration damping, the position error, etc.

Specific properties can be changed in real time and in this way critical states can be eliminated. And finally, the properties can be intelligently optimized to achieve an optimum state, minimize errors and power consumption, improve performance, reduce the environmental impact and make the module more intelligent. As the electronic integration of the module increases, so does its mechanical integration whereby its efficiency, reliability, operating accuracy and above all, machining performance increase.

The higher the requirements concerning stability, machining speed and machining precision, the greater must be the share of mechatronics and the excellence of its operation in machine tool modules. Numerous examples of the benefits resulting from the application of mechatronics in machine tool modules are presented in [9].

Increasingly more often machine tools are treated as autonomous machining units integrating the machine itself, the tool units, the highly efficient production jig and the workpiece machining procedures. The performance of such a machine tool is the resultant of the mutual interactions between all the components and the actions affecting the workpiece. Depending on their influence on performance, a proper weight should be attached to the improvement of the individual modules and the whole autonomous machining unit. If the autonomous machining unit (machine tool) is to attain a high development level and ensure highly productive machining, then the list of its features should look as follows:

The ranking of high performance machine tool features.

1. Robust (static, thermal, dynamic and life-cycle) features.
2. High efficiency.
3. Active precision.
4. Active settlement of positioning.
5. Integration tasks and technologies.
6. Flexible structure.
7. Robust interfaces.
8. Intelligence.
9. Self-compensation or errors and self organizing.
10. Real-time programmes.

Selected features can be assigned to the particular mechatronic modules whereby their rational development will be determined. It is also necessary to assign disturbances (errors) which need to be minimized to achieve high precision.

The combination of the basic modules at their integrated control level and their integration with the combined modules (being at a higher control level) represents the complexity of contemporary and future autonomous machine tools (Fig. 6) carrying out highly productive processes.

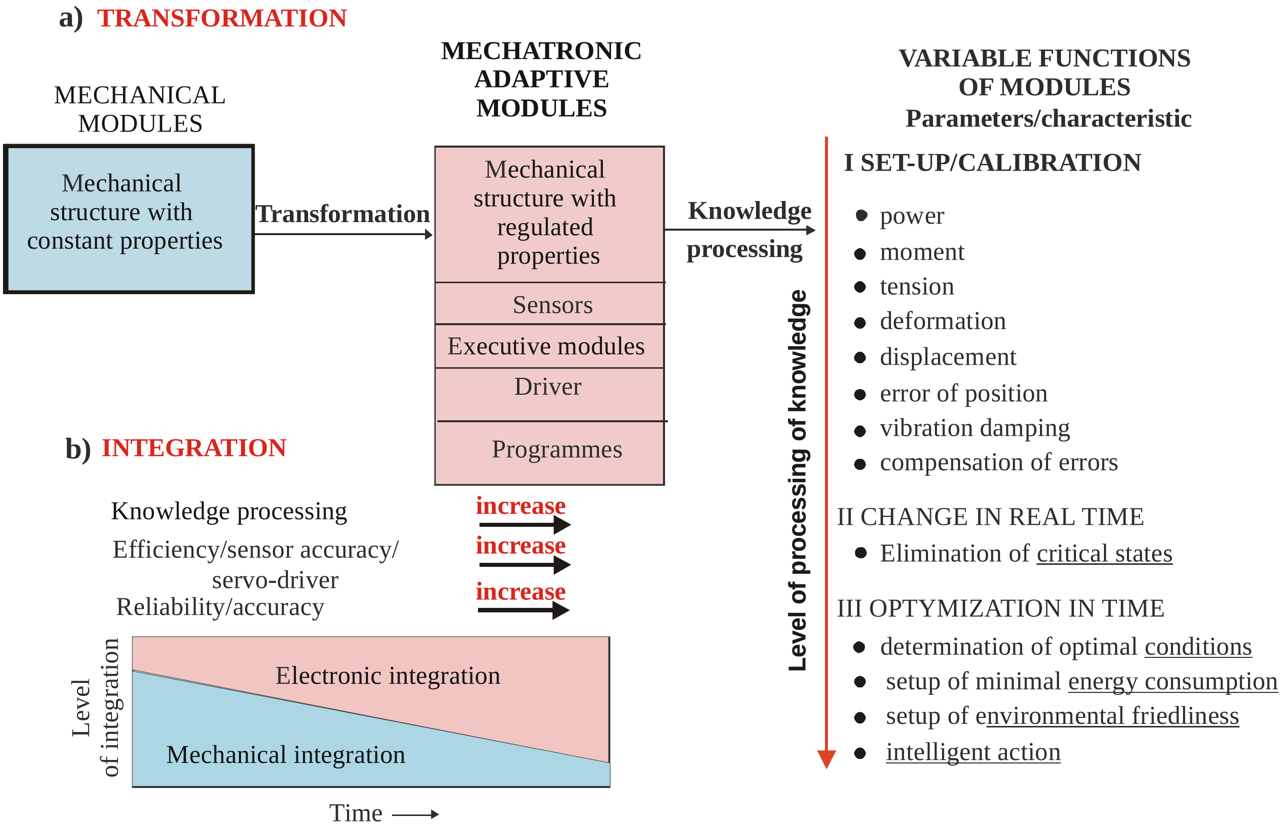


Fig. 5. Development of operational features of machine tool modules trough increased contribution of mechatronics and knowledge processing: a) transformation of modules, b) change of module properties with increased contribution of mechatronics

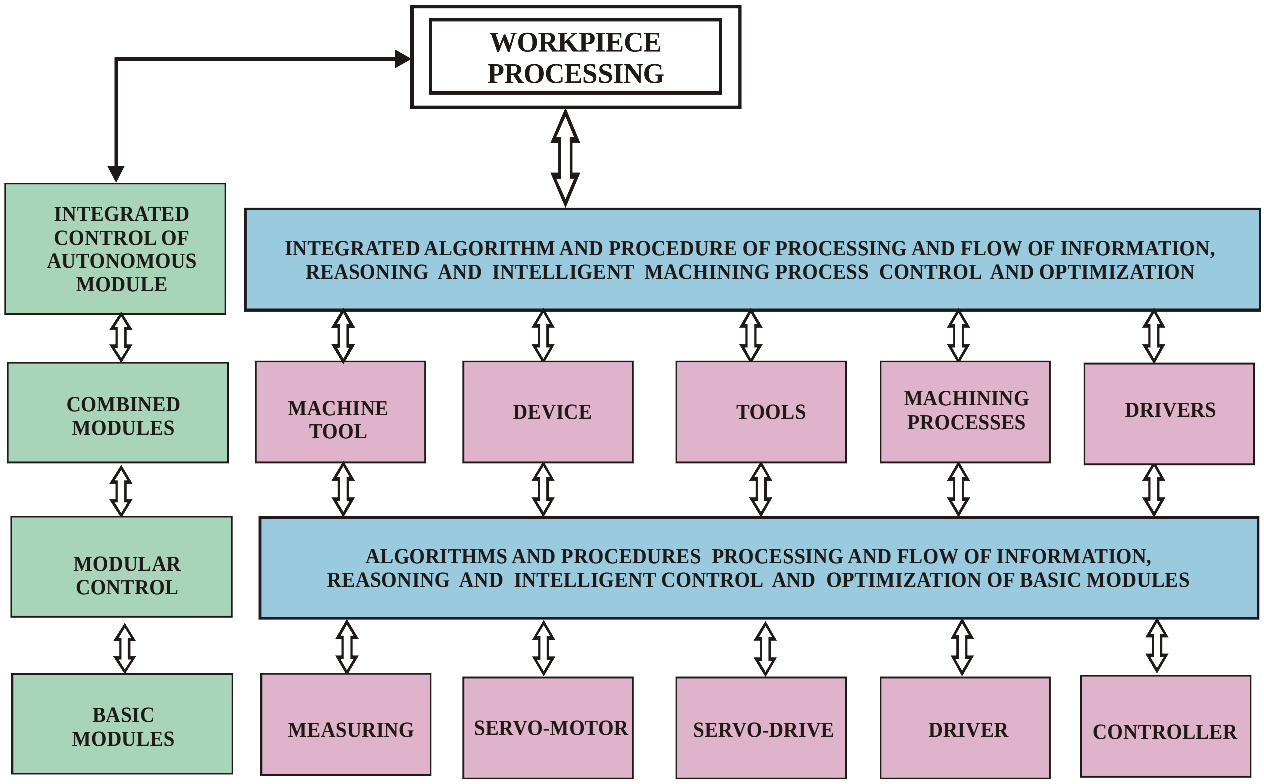


Fig. 6. Modular structure of autonomous CNC machine tool carrying out high efficiency machining process

The control system performs a special role. It is responsible for both the proper course of the processes and the elimination of all kinds of disturbances and extreme states. In order to be effective the control system must act intelligently, effectively preventing disturbances and promptly responding to them, preferably in real time. In the case of high-speed machining this is very difficult and requires special hardware and software. The two components must be improved with equal care, taking into account the increasing role of software. All the new solutions being created must be servicewise and environmentally friendly. The systems preventing tool/fixture collisions show the hallmarks of high intelligence. They are based on machine tool virtualization and real-time tool/fixture position simulation. A conceptual diagram of such a system is shown in Fig. 7.

Besides the structure of the modules, the machine tool’s general structure, and particularly its flexibility, greatly affects its performance. Figure 8 shows the kinds of this structure. The primary structure is a constant one with conventional kinematics based on controllable linear axes X, Y, Z and (temporarily added or constant) controllable rotational axes A and C . The controllable rotational axes are needed to machine workpieces complicated in shape. As regards turning, the main function is to position workpiece and tool spindles, while in milling the aim is to precisely control the change of the tool spindle axis position vector and to exactly determine the position of the blade’s tip for the precision shaping of the workpiece’s contour. Alternatively, the aim is to ensure controllable rotation of the table around one or two axes. A common configuration is 3 linear axes and 2 temporary rotational axes (3+2).

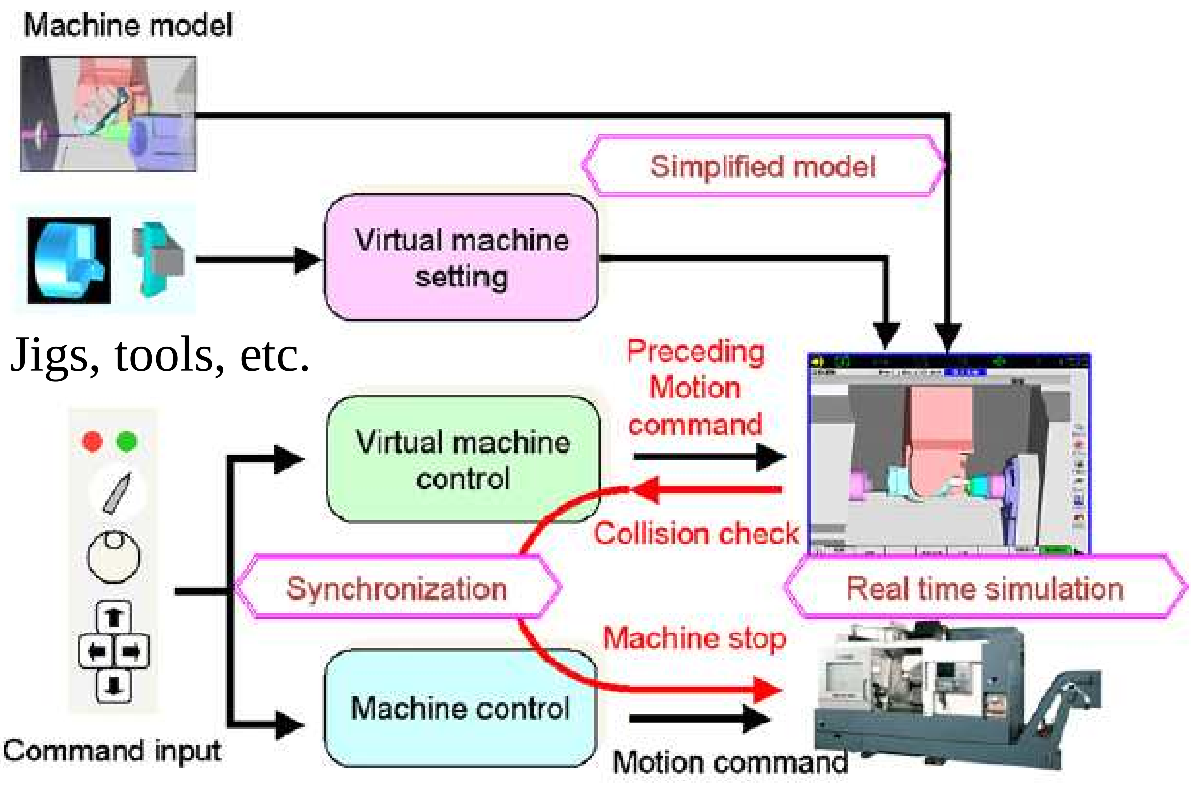


Fig. 7. Conceptual diagram of anti-crush system (Okuma Co.) [23]

The addition of the two rotational axes results in: a shorter milling cutter, easier machining access to workpiece hollows and steep walls, proper cutting with the milling cutter's cutting edge located at a proper distance from the rotational axis, simplified chucks and fixtures and simpler control (Fig. 9). Axial configuration 5 is universal, but in the case of typical constructions it uses a very large machine tool table surface area because of the large dimension of the device performing the controllable rotational motion of the table and swing motion. This a major drawback of this solution. Since the rotated bodies are large it is difficult to increase the rotational speed and ensure large displacements, high accelerations, high power and very low torque pulsation when surface smoothing.

In conventional medium-drive designs it is difficult to achieve high positioning and machining precision because of the clearances in the rotation mechanisms and considerable friction. These difficulties can be overcome by introducing direct drives (Fig. 10). In comparison with the previously achievable turning rotational speeds of 10-13 rpm (insufficient for precision turning), today it is possible to ensure high speeds of 40, 50, 100, 500 and as high as 12000 rpm, and optionally up to 20000 rpm (depending on the table's diameter, weight and mounting). Moreover, high torque, high accelerations and high stability can be ensured during long-lasting machining [10,11].

Thanks to the mounting and rotation of the table on only one swing axle pivot, small machine tool space is used, whereby this solution is often employed. It was also found that as high as triple reduction in milled surface roundness deviation can be achieved in this way.

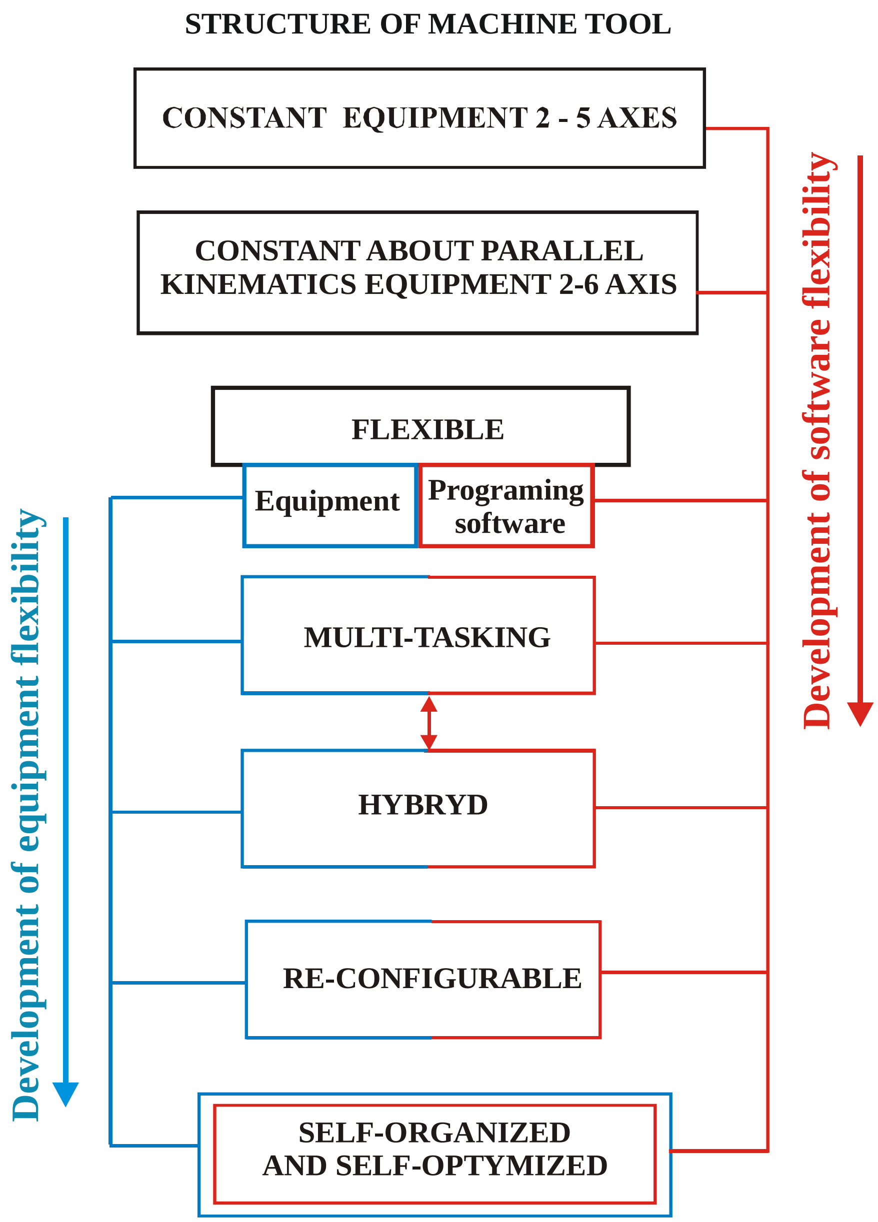


Fig. 8. Development of machine tool structure and its hardware and software flexibility.

The introduction of direct linear drives instead of, for example, helical gears turning in axes X, Y, Z, has also considerable advantages. Thanks to linear motors, large amplifications can be used and high positioning precision (0.2 μ at a command signal resolution of 0.1 μm) and high accelerations (1-1.5 G at a fast feed rate of 90 m/min) can be achieved. Linear motors make it possible to ensure low roundness errors of 5 μm at a feed rate of 30000 mm/min.

A big improvement in the dynamic behaviour of the machine tool (a reduction in vibration amplitude) can be achieved through the (increasingly popular) powering of slidable units with a drive in the centre of gravity (DCG) (Fig. 11).

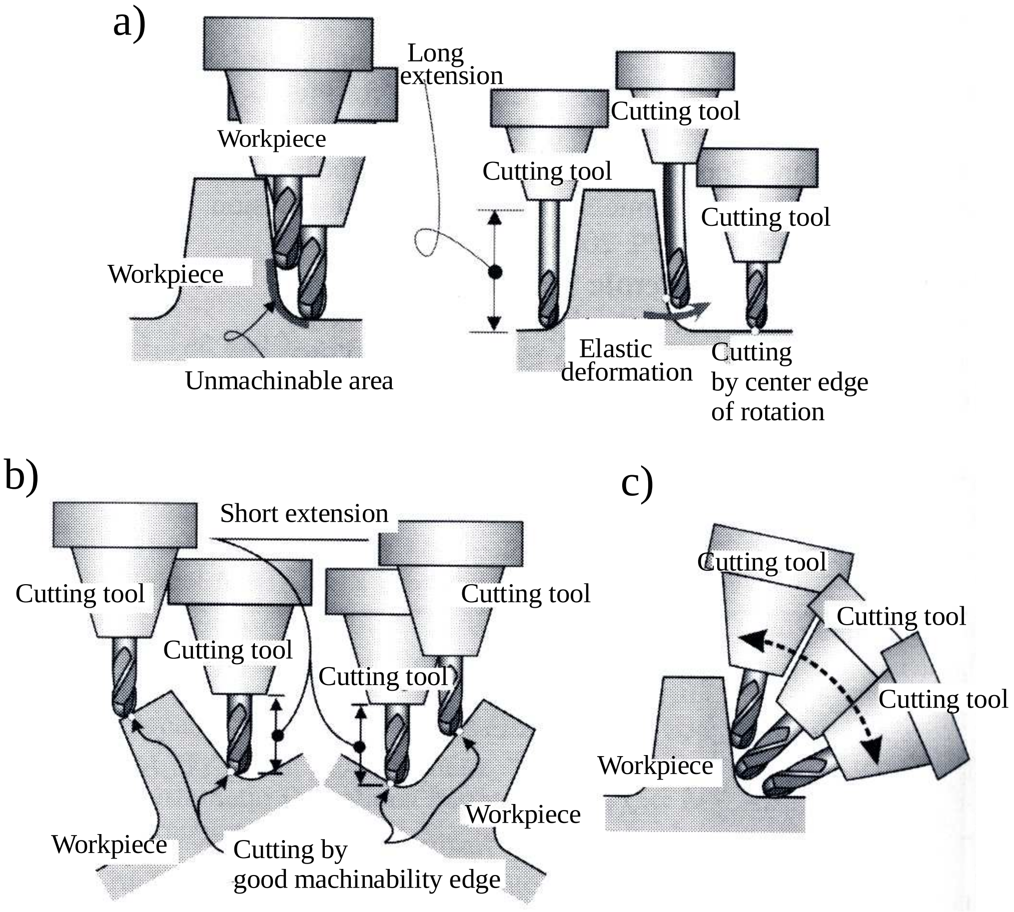


Fig. 9. Relationship between: a) 3-axis machining, b) tilted tool axis machining c) 5-axis machining [22]

There are both hardware and software limits to increasing the accuracy of representation of the workpiece contour described by CAD. In order to reduce the hardware constraints it is necessary to reduce or effectively compensate operatingdeformations caused by forces and thermal displacements. On the software side, the postprocessor should have an accurate model of tool axis and blade tip displacements with the compensation of errors (also the ones arising during machining). For each configuration of controllable axis modules the two displacement quantities should be transformed very precisely in real time. It is thought that a solution to this problem could be to use an accurate general kinematic model instead of the partial models. As regards the use of the inverse function and the prognostic function, it is thought that the prognostic function is more suitable for real-time error compensation.

Considerable benefits can be obtained through the use nano-CNCs which enable nano-interpolation, nano-feed, optimization of rotational speed for each axis and reduction of jumps and vibrations, which results in considerably higher machining precision. Then thanks to the use of very precise feed and rotational speed (particularly optimum speed and acceleration) values, surface nano-smoothing becomes possible whereby precision grinding is eliminated.

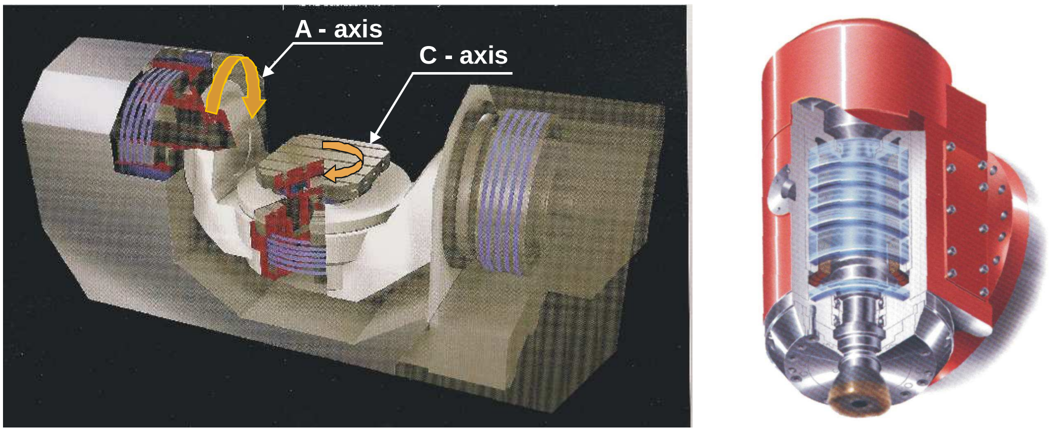


Fig. 10. Direct drive of A and C axis with high torque motors and milling spindle unit of turning centre with direct drive of spindle and its axis of rotation

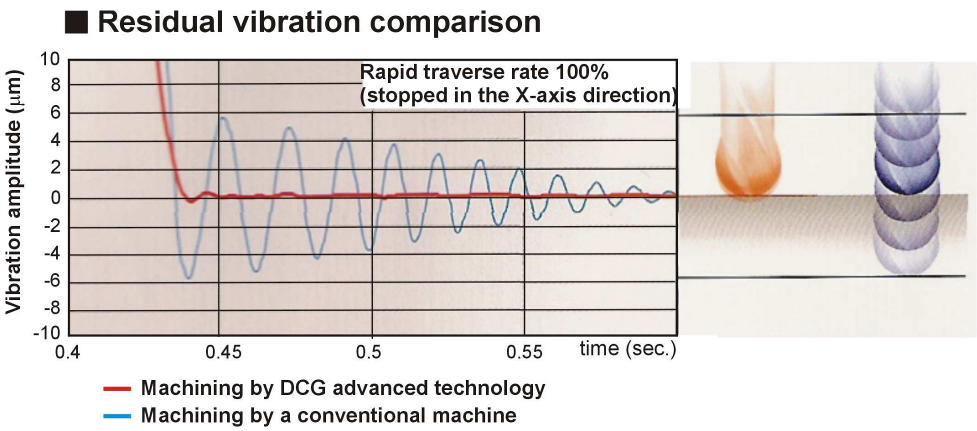


Fig. 11. Comparison of residual vibration for conventional and advanced DCG technology (Mori Seiki Co)

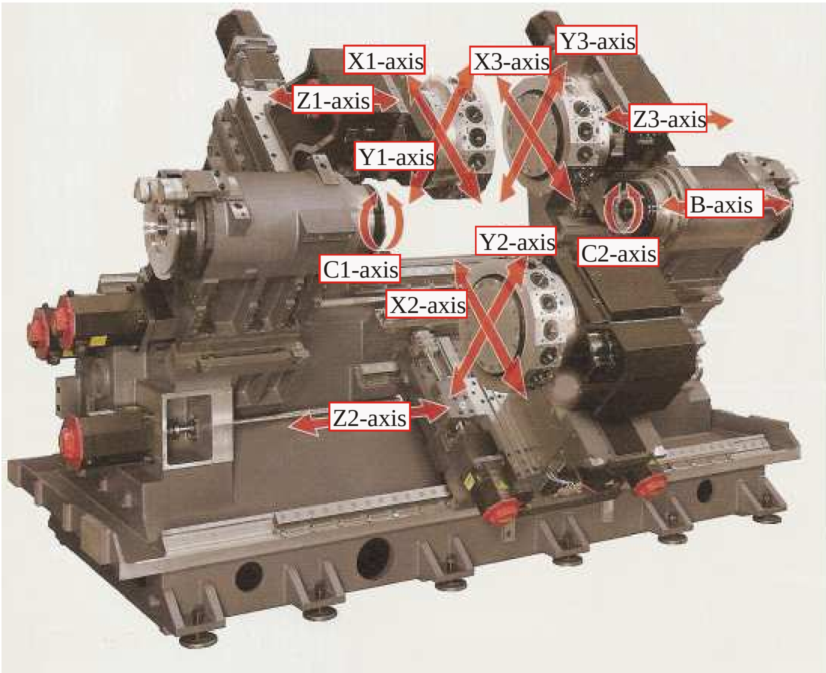
As the miniaturization of machine tools and their micromachining modules continues, the weight of the modules and their components decreases whereby the higher controllable axis speeds and considerably higher accelerations can be achieved. The higher the tool position control precision, the greater the ability to avoid collisions on the basis of simulations. Liebman M. and Vona M., A. (MIT) built a micro-machine tool which combines a linear controllable axis drive with a rotational one. Thanks to the innovative permanent magnet motor design, a linear acceleration of 8G, a rotational acceleration of 4500 rad/s^2, a resolution of 0.1 µm for a length of 2 mm along axis X and a resolution of 1 arcsec along rotational axis A per 180° were achieved.

The constant structure with parallel kinematics ensures up to 6 controllable axes. Originally it was predicted that thanks to the 6 axes and the high stiffness this structure will gain an advantage over the conventional structure. But because of difficulties in ensuring the required high machining precision such structures are not very popular (with a share below 5%). It is very difficult to ensure precise tool axis vector and tool tip position control.

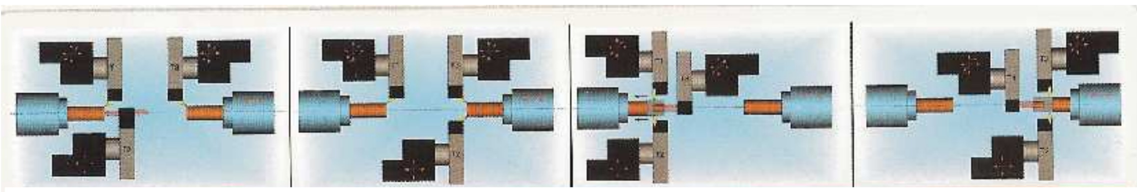
The source of the errors are the mechanical rotary joints between the linear drives, the headstock and the base, clearances, friction and the fact the stiffness changes drastically in the machine tool workspace and so within the usually complex workpieces. Moreover, such structures occupy very large space (much larger than the space occupied by conventional machine tools whereby their use for machining microelements is not rational.

Multitask structures are particularly widely applied in turning and milling centres. They enable ready-made or almost ready-made machining of workpieces very complicated in shape (which must meet stringent requirements as to dimensional-shape accuracy and surface smoothness) and machining of very hard materials.

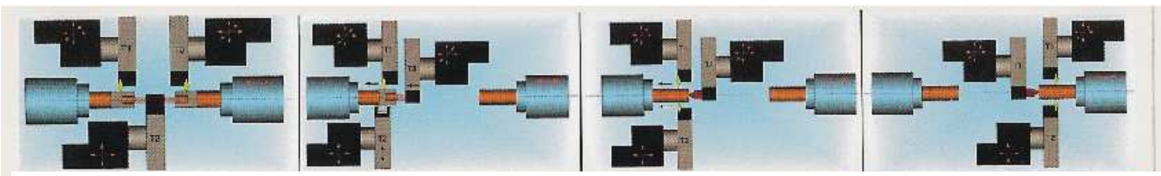
a)



b)



Each turret can work independently on spidle 1 or 2
Best cycle time thanks to continuous simulaneous machining



Tturrets can also operate as tailstock or support for long and shaft-type workpieces

Fig. 12. Multitasking turning centre with two headstock turrets: a) Structure, b) simulation of different simultaneous operation modes of three turrets of multitasking turning machine with 2 spindles

The task most often combined are: turning, milling and machining of holes and surfaces with complicated contours. In the case of lathes, more axes are usually added to the four (2+2) controllable axes as well as the milling function and other necessary functions are added whereby a highly organized turning centre is created. This solution can incorporate two workpiece spindles situated in one axis, and controllable axes C and C1 and axis B for angular setting of the direct-drive milling spindle. Another multitask turning centre solution consists of a machine tool with two headstocks with controllable axes C and C1 and with three tool heads which can hold tools with their own direct drives (e.g. for drilling and milling) (Fig. 12). The rational/optimal arrangement of the individual machining modules and their components, ensuring their unconstrained and collisionless coaction, is of fundamental importance for such machine tools.

The optimum arrangement of the modules must be supported with accurate operation simulation since the number of possible configurations is very large and the optimum configuration needs to be selected. It is important to use as small space as possible, ensure easy operator and service access and HSC and high machining precision. An expert system is needed to develop an operating strategy for such a complex machine tool. Its control requires efficient software enabling, among other things, direct transfer of data from CAD to CAM.

Figure 13 shows how to use a virtual model for generating a tool trajectory. In order to generate a precise tool trajectory one needs a controller with a proper architecture, highly efficient algorithms and multiaxial interpolation.

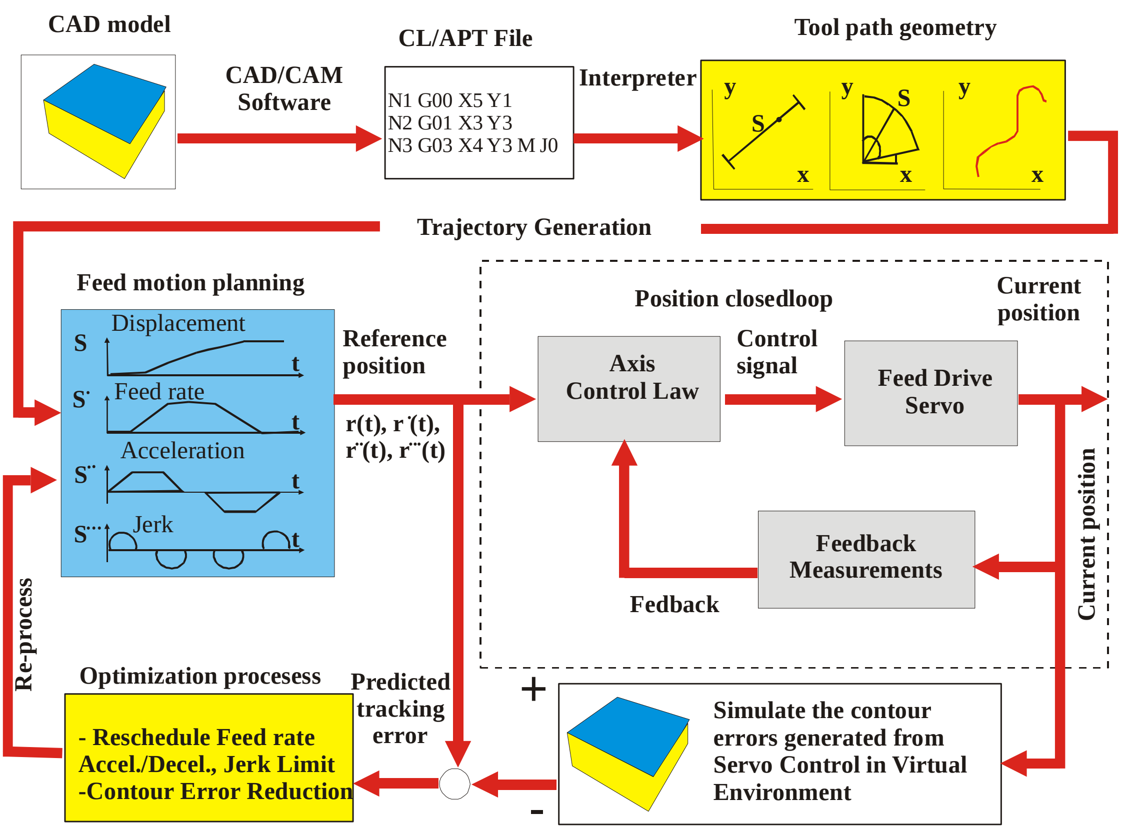


Fig. 13 Virtual model of trajectory generation and axis control [11]

Currently maximum 10-24 tool trajectories can be simultaneously simulated, which seems to be sufficient. The problem still is how to ensure high thermal and dynamical stability and proper stiffness of such complex structures and to eliminate disturbances and the adverse effect of vibrations. Also high speed and acceleration stability needs to be ensured.

Hybrid structures. Multitask machine tools often assume a hybrid form. But the expansion of a complex multitasking structure is costly. Therefore a cost-benefit analysis of the hardware and software expansion and of the expected increase in machining performance is needed. Also an error analyses covering both complex multitasking hybrid structures and reconfigurable hybrid structures should be made.

A hybrid structure is usually created by adding modules/devices for the laser machining or laser aided machining of materials which are hard to machine. When there is a need to shape complex contours of thin-walled elements, forming modules, and in special cases, EDM or ECM modules are added. The integration of machining modules and abrasive
machining modules does not pose any major hardware or software difficulties. As regards other types of modules, their integration requires additional complex design solutions, but the machining performance significantly increases (sometimes several times).

The reconfigurable structure came to being to facilitate a change of machining technology when certain processes are to be replaced by new more effective ones or when the product is to be changed. The reconfiguration philosophy allows one to keep highlyefficient machining modules, which brings considerable economic benefits. The longer the product lifetime, the more often the technology needs to be changed and the greater the benefits which a reconfigurable machine tool (machine tool structure) brings. This is particularly true of multitask and hybrid machine tools. Having a set of the necessary machining modules the user should be able to inexpensively configure and reconfigure them using the available optimum hardware and software solutions and his/her own technical personnel. This means that a reconfiguration should be planned and carried out on the basis of a specified set of load-bearing structure components and robust interfaces and execution and control modules. The user must have a model enabling him/her to simulate the needed optimal hardware and software configuration. The functions of such a simulation system are presented graphically in Fig. 14 [12]. If reconfiguration is to be effective, the whole set of modules (meeting the criteria for easy and correct reconfiguration and for the proper static, dynamic and thermal behaviour) must be optimized. Thus a virtual system (easy to master and use) supporting the reconfiguration process plays a key role.

The development of effective machine tool reconfiguration is determined by the development of accurate modelling, simulation and optimization. The collection of knowledge about the factors having a bearing on module design, which determine the desired proper behaviour of the structure being reconfigured, plays a vital role here. The configured control system should take over the appropriate tasks of controlling the operation of the modules and monitoring and compensating errors.

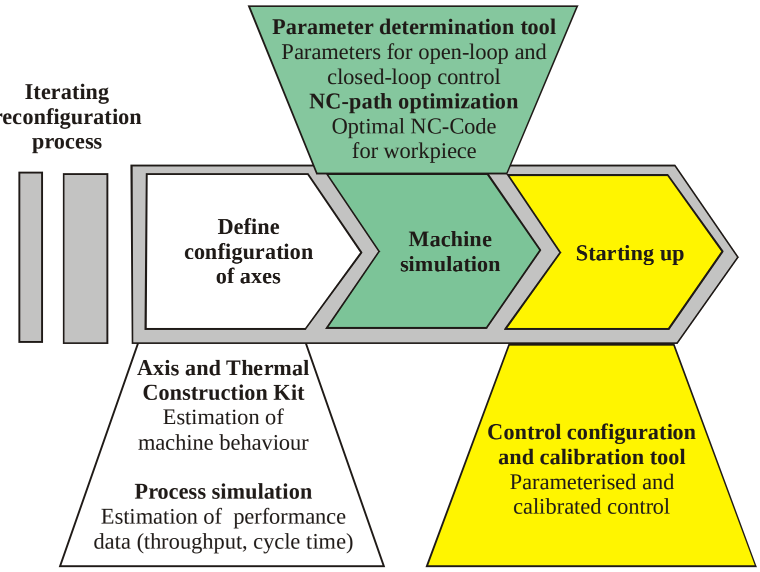


Fig. 14. Functions of virtual assistant for machine tool reconfiguration [12]

4. SPINDLE ASSEMBLIES

Machine tool spindle assemblies are modules which determine machining performance. High machining performance is possible thanks to spindles which develop high or very high speed, torque and power needed to create proper conditions for the precision HSC and roughing of specific materials in accordance with the requirements and trends.

Increasingly more often the requirements apply to materials which are hard to machine, precision and high precision machining and environmentally friendly machining. Machining and feed speeds used in various types of machining constantly increase (Fig. 3). Spindle assemblies used for HSC are based on ball bearings with small diameter and weight ceramic balls characterized by a low coefficient of friction. The small weight is necessary to reduce the centrifugal forces and to achieve high accelerations and acceleration rates, needed to reduce idle time. The low coefficient of friction is needed to minimize power losses (mainly determined by the lubrication method). It also determines the permissible maximum rotational speed of the bearings. This speed is expressed by high-speediness parameter $d_m n$ where d_m is the average bearing diameter and n is the rotational speed of the spindle. The limit values of this parameter depend on the spindle assembly design, the type and number of bearings in the front and back nodes, the loading of the node (particularly the front one) by cutting forces and the (constantly improved) lubricating medium and method (Tab. 1).

Spare (minimum) lubrication ensuring minimum power losses is preferred [13,14]. In the case of (minimum single) greasing, $d_m n$ currently reaches maximum $2 \cdot 10^6$. For minimum air-oil lubrication, $d_m n$ amounts to $3.5 \cdot 10^6$ and for minimum injection lubrication it amounts to $4 \cdot 10^6$. Injection lubrication must ensure the supply of oil to the friction zone (oil wedge) which is counteracted by the centrifugal forces accompanying high rotational speeds.

Table 1. Bearing lubrication systems application conditions

Kind of lubrication	General application	Permissible values of high speediness coefficient $d_m n$	Application to machines
Grease	Ultra high speed and high load of angular contact ball bearing sets DT sets DB sets DBD set DBB set	 $2.0{\cdot}10^6$ $1.5{\cdot}10^6$ $1.3{\cdot}10^6$ $1.2{\cdot}10^6$	Machining centre, grinding machine, high frequency spindles NC lathe, NC milling machine, machining centre
	High rigidity double row cylindrical roller bearings	$0.8{\cdot}10^6$	NC lathe, NC milling machine, machining centre
Oil-air lubrication	Ultra high-speed and high load of angular contact ball bearing sets for ceramic rolling elements DT sets DB sets DBD set DBB set	 $3.5{\cdot}10^6$ $2.5{\cdot}10^6$ $2.2{\cdot}10^6$ $1.8{\cdot}10^6$	Machining centre, grinding machine, High frequency spindles NC lathe, NC milling machine, machining centre
	High rigidity double row cylindrical roller bearings	$1.0{\cdot}10^6$	NC lathe, NC milling machine, machining centre
Oil injection lubrication	Super high-speed of bearing nodes. To be used only for special design of bearings with ceramic rolling elements and for ultra rotational speed.	$3.5{\div}4.0{\cdot}10^6$	HSC machining centre, grinding machine, high frequency bearing units
Eco – friendly oil – air lubrication	The highest speed NTN ULTAGE bearing set	$5.0{\cdot}10^6$	HSC machining centre

Conventional injection lubrication is characterized by the rate of oil flow to the bearing race in the order of 3.1 l/min, whereas in the case of air-oil lubrication this rate of flow amounts to merely 0.03 ml/min and the oil does not escape from the bearing and so it does not degrade the environment. A very high rate of flow results in high power losses and a high bearing operating temperature. The latter does not increase only when there is intensive cooling and the oil flows through the bearing (Fig. 15).

Intensive R&D has resulted in new ultra-precision ULTAGE bearings characterized by high speediness coefficient $d_m n^{\cdot} = 5{\cdot}10^6$. The bearings are made of a special wear resistant material, have ceramic balls and a minimum oil flow rate similar to that in air-oil lubrication, and oil is supplied to the balls through the action of the centrifugal force (Fig. 16). Thereby the minimum lubrication conditions are maintained, ensuring small temperature increases and low power losses, vibration damping by oil falling on the balls and reduction in noisiness by 8 dB. Moreover, the lifetime of the bearings is over ten times longer than that of the intensively lubricated bearings which have been used so far. In addition, the oil feeding and cooling system lubricates the bearings and cools them externally as well as cools the motor, which reduces the operating costs. One can expect that future innovative bearing designs and lubrication methods will result in further increase in the value of parameter $d_m n$. The current highest rotational speeds of machining centre electrospindles reach 42000 rpm, 54000 rpm and even 60000 rpm (for carefully balanced spindles and rotating elements).

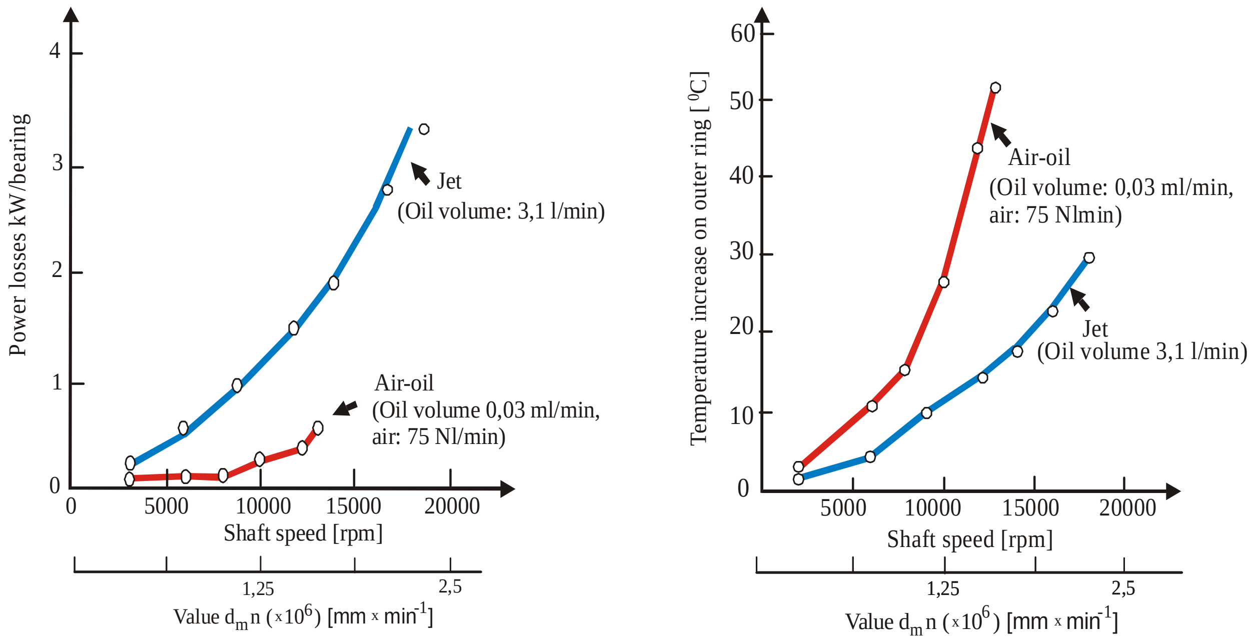


Fig. 15. Comparison of power losses and ring temperature for air-oil and injection lubrication (Bearing: 2LA-HSE020, bore 100 mm, outside diameter 150 mm, Rolling element: Bearing steel) [25]

A major drawback of all the spindle drives is the fact that as rotational speed increases, torque significantly decreases. This is shown in Fig. 17. But in machine tools, especially multitask ones, a high spindle torque is required to ensure high machining performance and a power excess for stable machining. Therefore the spindle often must be a multitask one. Yamazaki et al. [15] solved this problem by connecting an additional high-power motor via a coupling to the electrospindle (Fig. 18). The connected motor is short, hasa large diameter and it is equipped with a ring cooler. This solution ensures a torque increase of 80% and a power increase of 104%. In the test machining only 37% of the torque was actually used, whereas in the case of the electrospindle alone, 72% of the torque was used. Thanks to the use of the double motor, high rotational speed stability during machining was obtained whereby the lifetime of the tool and resistance to vibration considerably increased. Thus the performance of the machining centre equipped with this motor increased.

In many machine tools, particularly milling centres, the spindle through its behaviour in operating conditions directly affects the dimensions of the workpiece and the quality of its surface.

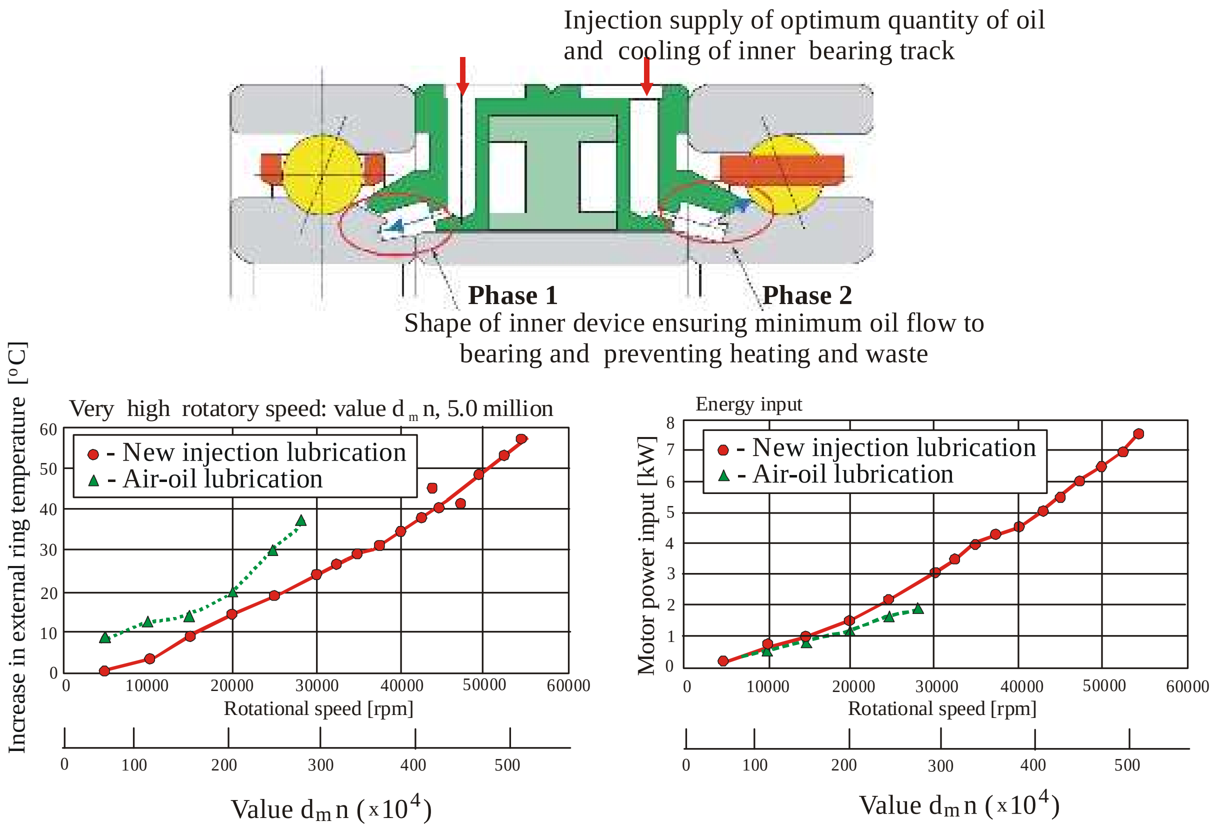


Fig. 16. Temperature increase on outer bearing ring and power consumption for new economical injection lubrication and air-oil lubrication (ULTAGE bearings) [19].

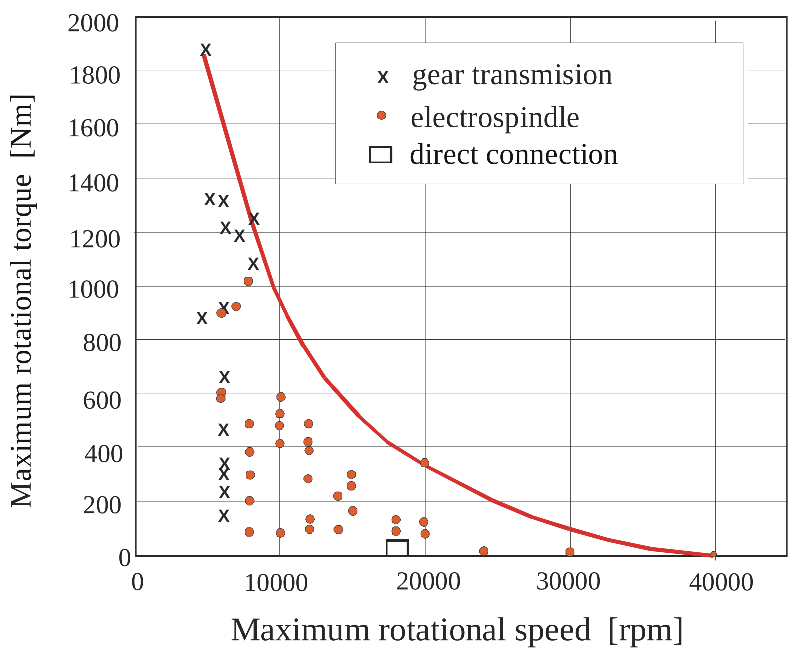


Fig. 17. Range of application of different spindle drives and transmitted torque versus rotational speed [15]

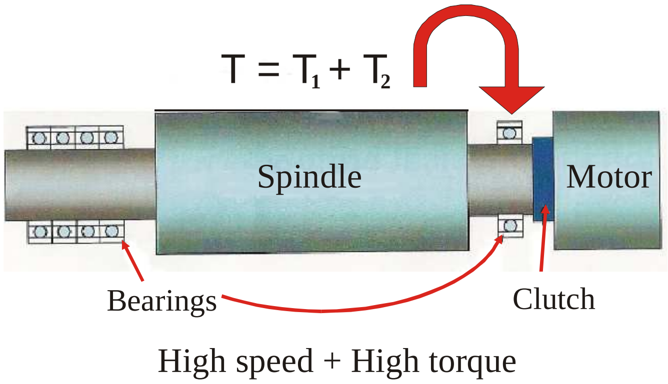


Fig. 18. Dual drive spindle system for increasing torque by means of high - power motor [15]

In order to ensure high and repeatable machining precision, machine tool manufacturers put a lot of effort into reducing spindle displacements. The main cause of such displacements are heat sources whose strength strongly depends on the power losses in the spindle assembly (in the case of an electrospindle, the power losses in the bearings and in the motor). Also changes in the shop floor temperature significantly contribute to the machine tool thermal error [16]. Spindle displacements caused by power losses are minimized by cooling the bearing retainers and the motor stator and through compensation based on calculation models and displacement simulations as well as on the measurement of temperature in the measuring points determined from the model.

Many leading producers of highly productive machine tools compensate errors due to changes in ambient temperature. They also compensate spindle displacements originating from internal heat sources. Before they are compensated, thermal errors are always minimized on the basis of the modelling and simulations of heating and volumetric displacements in the whole workspace. As a result, machine tool thermal symmetry is obtained. The knowledge needed for this purpose is acquired from research and experiments conducted for many years. A strategy for the thermal improvement of machine tools, developed by the authors of this paper, is shown in Fig. 19.

The effectiveness of the methods of compensating the axial displacements of spindles and whole machine tools is still far from the desired one, particularly as regards precision and high-precision machine tools. The displacements are repeatable to a small degree and the compensation formulas/algorithms do not encompass all the displacement related phenomena because of their high complexity.

Being aware of the above problems machine tool producers try to increase the thermal correctness of machine tool structures not only through thermal symmetry, but also by creating natural conditions conducive to heat transfer, minimizing the heat flows which cause undesirable deformations, using carefully matched forced cooling and so on. Forced cooling, which can be applied to: the bearings, the electrospindle motor stator or the swivel table, the inside of the spindle and the rolling screw, the ball nut and even parts of the housing walls, creates new problems relating to the accurate modelling of the transferred heat and to the control of the cooling agent temperature. Such cooling is applied by many machine tool producers, but its accuracy is still too low and further research in this field is needed. Such innovative solutions as the compensation of displacements within the structure by means of active elements in the form of piezoelectric actuators seem sensible, provided that they do not compromise the static and dynamic properties.

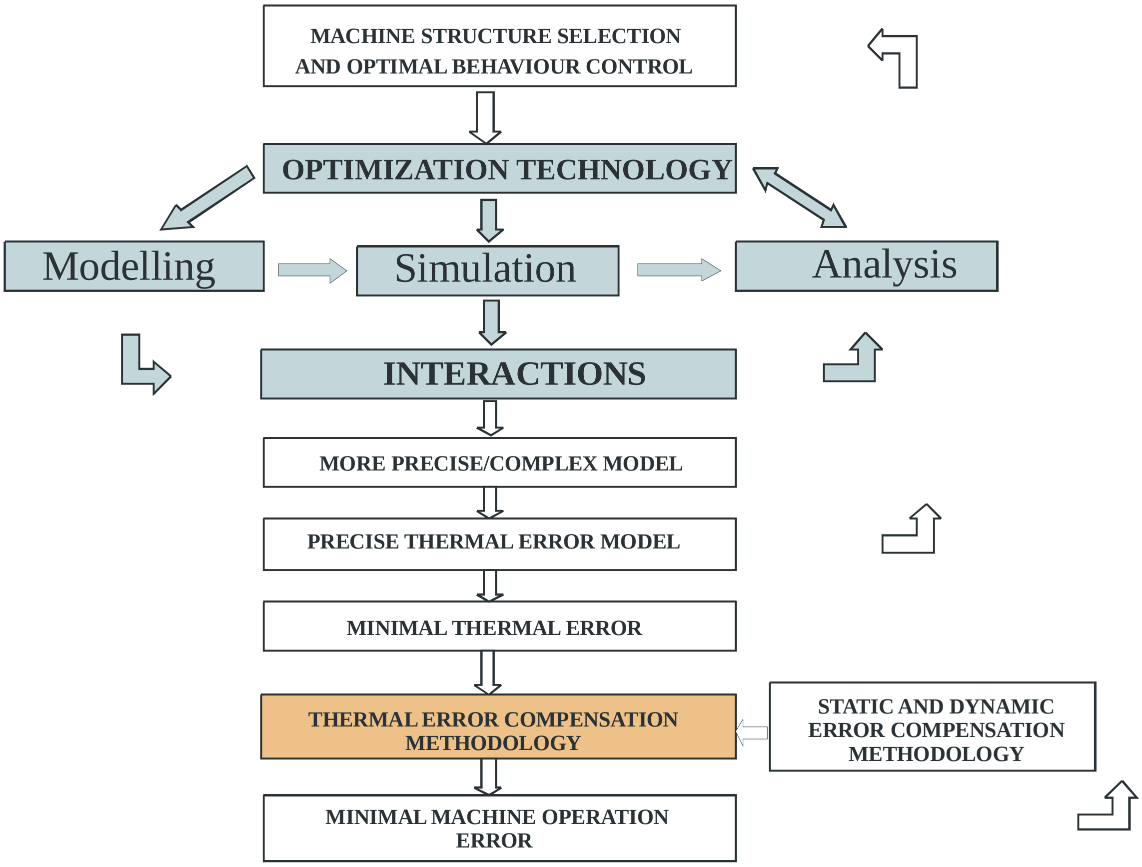


Fig. 19. Thermal error impact minimizing methodology, acc. to in-house study

Each such measure in order to be effective for a given machine tool structure must be supported by accurate modelling, a multivariant analysis, simulations and optimization in close collaboration with the machine tool designer and the process engineer.

Also the centrifugal forces acting on the spinning elements of the spindle assembly, the spindle itself and the inner bearing rings and balls can be a source of axial spindle/spindle tip displacements relative to the machine tool table/the workpiece. The operating conditions of the balls, the tension of the bearings and the length and diameter of the inner rings and the spindle change in high-speed spindle units subjected to centrifugal forces. Moreover, the spindle displaces as the contact angles of the bearings change. Figure 20 shows the displacements of the spindle front end relative to the table (S_h) as the rotational speed increases, and the shares of spindle support shortening ΔA and spindle tip shortening ΔB in the displacements for a spindle unit whose bearings are spring tensioned by means of a slidable sleeve [17]. One can see what spindle tip displacements at a given rotational speed (relative to standstill) and what changes in displacement as the speed changes can be expected. The possibility of modelling and compensating such displacements is essential for increasing machining precision and performance.

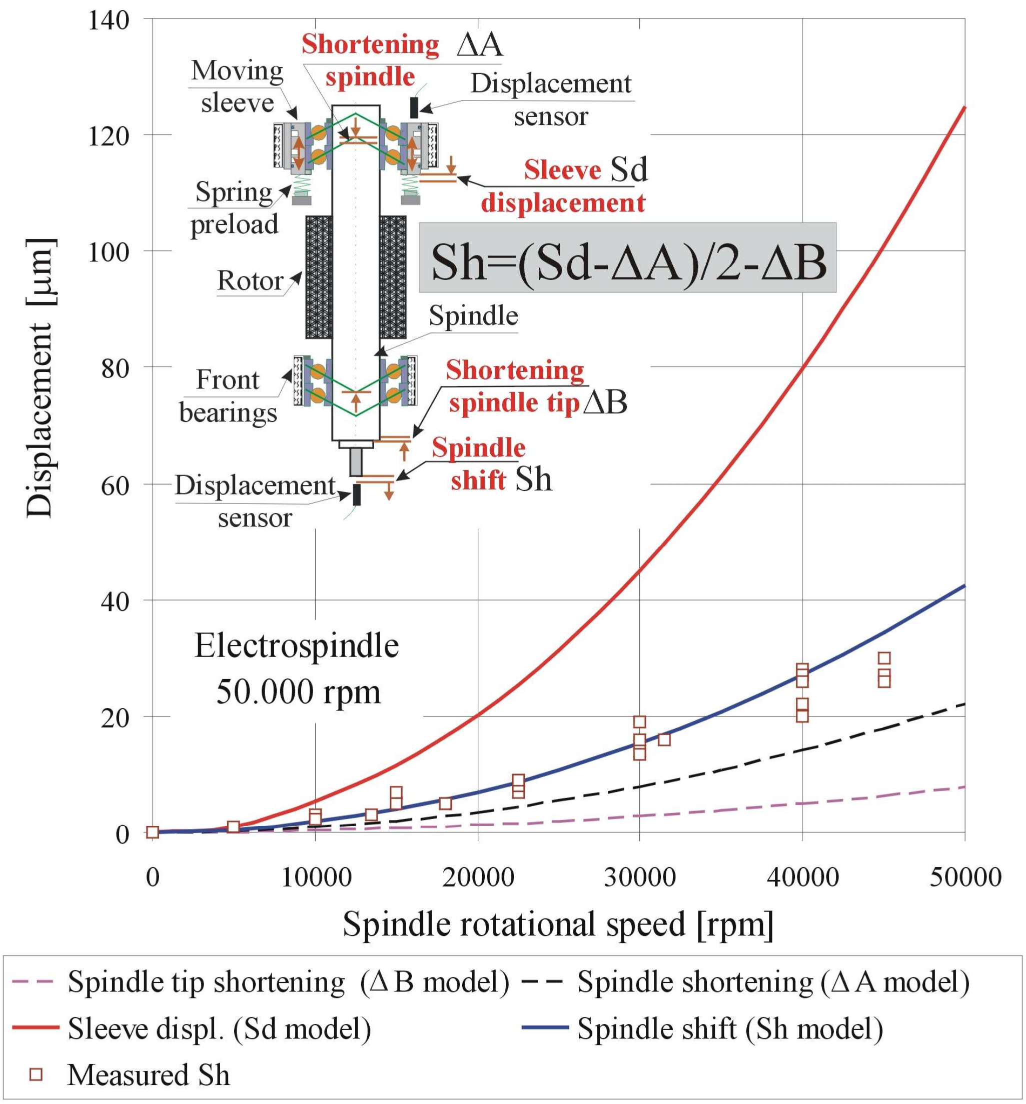


Fig. 20. Forecasting and verification of high speed spindle axial displacements [17]

The spindle displacement which greatly affects machining precision is spindle elongation which increases over machining time. This displacement and the thermal displacement of the housing (caused by internal and external heat sources) add up [16]. Figure 21 shows such spindle tip displacements along axis Z of a high-speed machining centre. But in order for compensation to be effective the compensated errors should be repeatable, which depends on both the machine tool design (and particularly on the design of the spindle unit) and the machining and assembly technology. In order to effectively compensate thermal errors the thermal behaviour of the whole machine tool must be improved [20, 21].

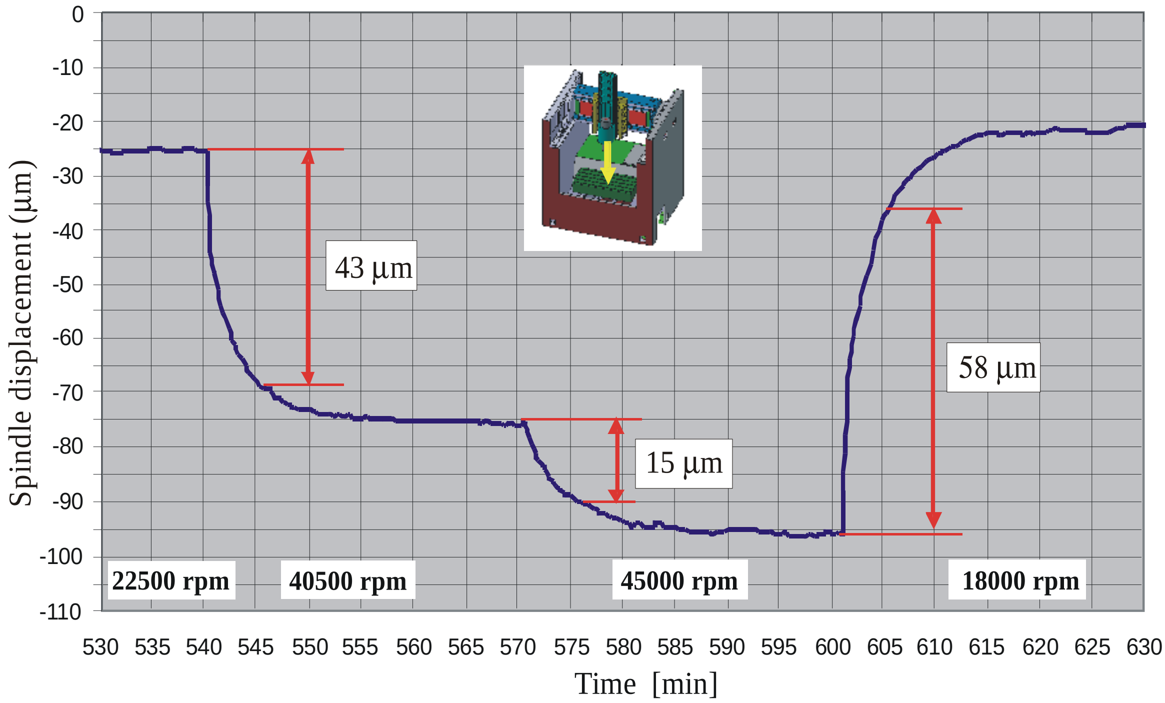


Fig. 21. Rate of displacement after change of spindle rotational speed

With the large increase in spindle rotational speed, necessary for the machining of many materials used in, for example, aeronautical structures, there is a need to increase the dynamic stability of the assemblies involved, including the chuck and the tool. Regenerative chatter vibration should be eliminated not by reducing the rate of feed and the rotational speed, but by properly controlling the speed, even in the case of large machined layer cross sections. This opens a way for obtaining high precision. Such research is also conducted for spindle assemblies, particularly their bearings [24].

5. MEASUREMENT MODULES

The accuracy of measuring the linear and angular trajectories is of great importance for increasing machining precision. Incremental or absolute digital optical scales (Fig. 22) [18] are mainly used for such measurements. In HSC machine tools with very high feed rates (in the order of 100 m/min) and very high accelerations (05-2 G, for slow machining processes this acceleration does not exceed 0.1 G) it is important to precisely measure the trajectory. This does not pose any difficulties at low speeds. Optical scales ensure measuring accuracy of ±0.5 µm at a rate of 7.6 m/min. As the rate increases, the accuracy decreases.

Recent studies [18] show that absolute magnetic scales operating on the principle of magnetic resistance (Fig. 23) are capable of very high resolution (in the order of 10 nm) and a repeatability of 20 nm (resolution in optical scales amounts to 0.128 µm) and provide results in real time.

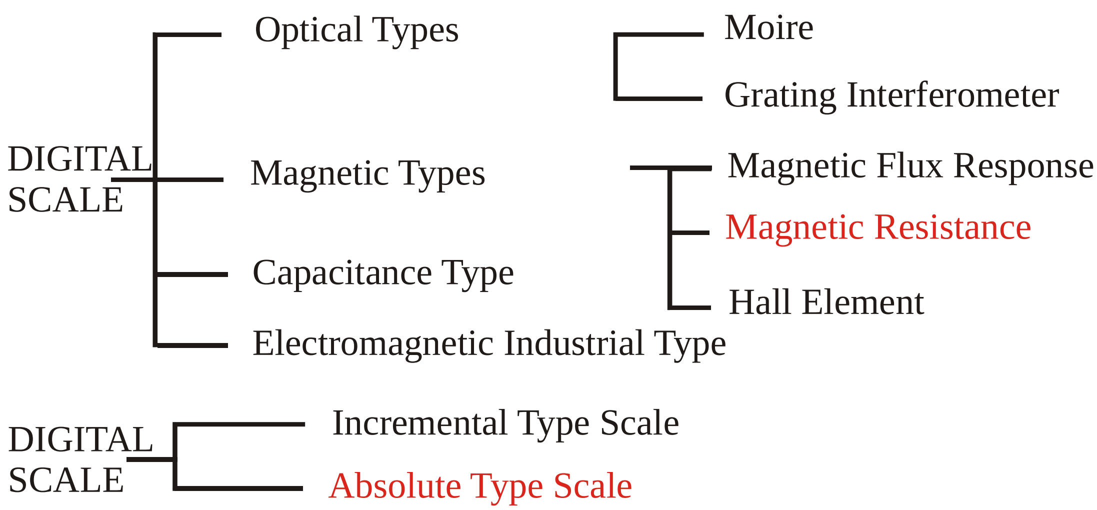


Fig. 22. Types of digital scales [18]

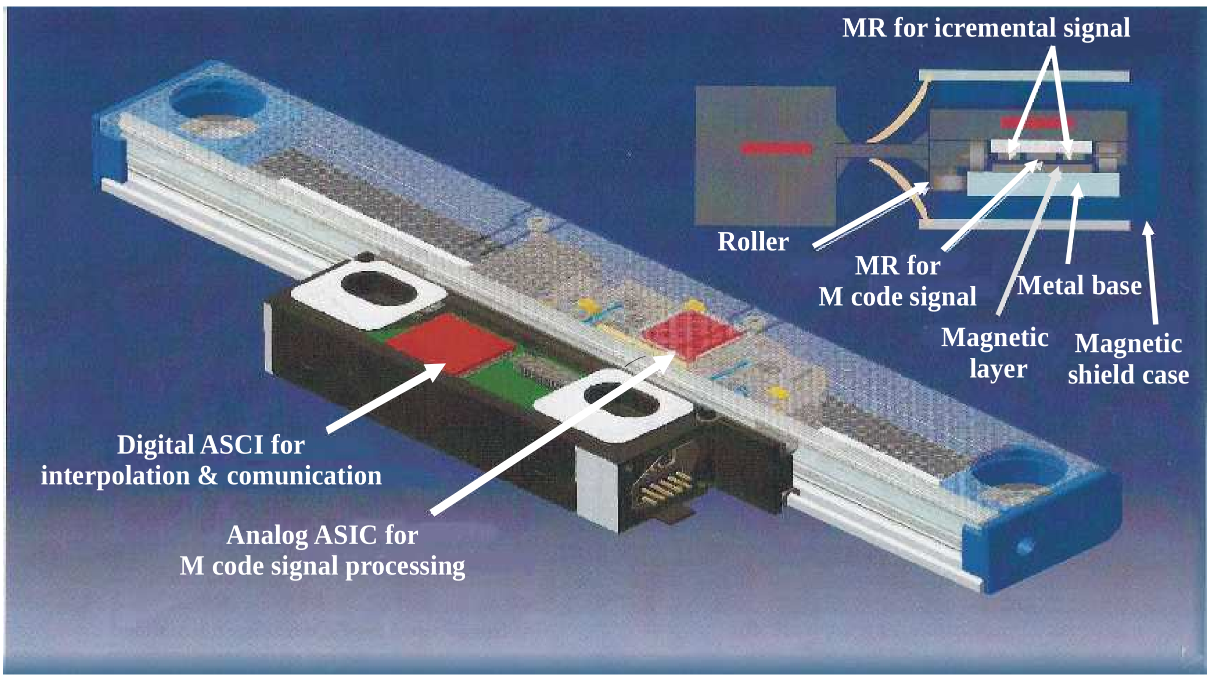


Fig. 23. Absolute magnetic scale design for precision machine tools with 10 nm resolution [18]

Their sensitivity is five times higher than that of optical scales, interpolation precision – λ/1200 at 8000 rpm, permissible rate of feed – 200 m/min (2000 rpm for rotary converters/encoders), power consumption – 160 mA, operating error – 1.5 μm and repeatability – 0.02 μm. The scale is not sensitive to cooling-lubricating fluids and is incorporated into the table of a grinding machine. The above developments open a way for precise trajectory measurements in HSC machine tools.

6. CONCLUSION

Because of the very fast development of materials engineering and the increasing precision and complexity of products, machining technologies and machine tools must meet very high and fast changing market demands. The role of mechatronic and software solutions in machine tools grows. Such solutions are the basis for increasing the flexibility of machine tools and delivering products to market at reduced production costs. The improvement of the basic machine tool modules, which constitute the measuring units of the trajectory, is of key importance. It is also vitally important to increase machine tool lifetime, which can be achieved through the development of intelligent machine tool functions, self-diagnosis, self-supervision, error compensation and self-servicing.

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