Machine tools for future oriented production

N. Hennes
DS Technologie GmbH, Werkzeugmaschinenbau GmbH, Mönchengladbach, Germany

1 Introduction

Modern production companies have to respond to shorter product life cycles and rapid changes in product properties with flexible production, high delivery reliability and low production costs. Such qualities are in large part guaranteed by appropriately designed machine tools. Whereas machine tool development in recent years was marked above all by continually higher speed requirements for machines and components, other - in part opposing - machine requirements are now becoming the focus of the users' attention.

A basic precondition for elaborating machine tool concepts is that they have to meet process requirements (see Figure 1). Workpiece accuracy, piece numbers and process data determine in large part the required properties of the machine tool. In addition to process-induced machine requirements, the range of services offered by the machine manufacturers is an increasingly important factor for purchasing decisions. Already today, many machine tool manufacturers offer comprehensive services for operator training, preventive maintenance and machine repurchasing in addition to the actual machine technology, and are thus automatically more integrated in the customer's overall production process.

Efficient and low-cost production can be achieved by a high workpiece output (on the machine side) and therefore by fast machining operations. What is particularly important is that the user has be able to respond quickly to frequently changing demands of the market. In this respect, “flexible” production machines that can be easily and quickly adapted to the changed production processes, can make a decisive contribution. In addition, next to investment costs, holistic cost considerations about the life cycle of a machine are gaining more and more significance and lead to analysis of life cycle costs (LCC). Within the scope of these considerations, additional cost advantages can be attained if machine availability and reliability can be increased by a simple
machine design, e.g. using subassemblies with low fault susceptibility and by reducing the number of machine components.

![Figure 1: Factors influencing the purchase decision](image)

Against this background, there is a recognisable trend that the machine users are increasingly delegating the responsibility for manufacture to the machine suppliers. If in the past, only the product “machine” and repairs were covered by the warranty, nowadays many machine manufacturers supply complete manufacture packages including machine, process technology and services around the product [1]. In the end, this could mean that the user no longer pays for the machine itself, but just proportionally for the products made on the machine. Whether this step with all its consequence will be put into practice, one cannot foresee. For the machine manufacturers, this nevertheless means already now changing from machine supplier to production supplier.

This open up for the machine tool a field of conflict because of opposite requirements at various times. Fast and accurate, yet at the same time simple and flexible machines, will guarantee technically and economically efficient production in the coming years from the user’s viewpoint.

2 Process-oriented machine concepts

The requirements make it clear that a machine design that makes good economic and technological sense can only be achieved in conformity with the boundary conditions for production process and production costs. The following principle is applied: *process and costs define machine and components*. It is possible to provide machine concepts that meet the requirements “flexible and simple, fast and accurate” with special attention focused on the workpiece and the manufacturing process.
2.1 Hybrid kinematics for production of integral aircraft components

The aeronautical industry makes particularly high demands on the structural components. Many safety-relevant and heavily stressed parts are therefore made of plate material. The integrally constructed component from the fuselage area of the Eurofighter is characterized by the fact that the quantity of metal removed is as high as 95%. Machining is carried out to 80% with 5 axes and maximum tool setting angles up to 40° (Figure 2) [2, 3].

These complex integrally constructed components were made in several work steps on different machines in the past. Roughing down is generally carried out on multi-spindle 3-axis machines. Each component has to be moved to a 5-axis machine for finishing operations. This has a negative effect on the processing time and quality of the components. Machining with swivel angles of more than 30° cannot be carried out on conventional machines, or only with the aid of special tools. According to the path contour, the tool swivel axes (especially with small tool settings) are subjected to very high angular velocity and angular acceleration rates.

Technical Data

- Dimensions
  - Length 1,920 mm
  - Width 1,161 mm
  - Height 116 mm
- Material AL
- Quantity of metal removed 95%
- No. of pockets 104
- Min. wall thickness 2 mm
- 5-axis machining 80%
- Weight of finished part 17,4 kg
- Max. required tool setting angle 40°

Figure 2: Integral-construction fuselage for the Eurofighter
(Source: EADS Augsburg)

The linear axes with the required speed cannot carry out the kinematically induced balancing movements, so that the feed motion at the tool drops in part to zero. In the case of overloading, not only do the main spindles often sustain damage but also the complex swivel axes are damaged or destroyed. Rotary transmission leadthroughs and rotary transmitters are particularly critical components. Accordingly, repair of attachment heads, and machine downtimes for maintenance, replacement and repair constitute a large cost factor. In view of increased availability of the overall plant and reduction of maintenance costs, it was the aim to avoid the drawbacks of angled-axis and fork heads by using an alternative solution for the swivel motion.
Based on these considerations, a machine concept was developed as a 5-axis hybrid kinematics consisting of a series-produced 2-axis machine of framed column construction in combination with a 3-axis tripod attachment head (Figure 3). The tripod attachment head consists of three linear drive units that are connected to the spindle platform via rockers and swivel and ball joints. The Z-motion is realised by the synchronous movement of all drive units. Single and double motions of the linear axes allow the spindle unit to swivel by A and B of ± 40° each. The linear axes driven by means of rack and pinion (X) and ball bearing spindles (Y, Z) allow travel speeds of 65 (X) and 50 m/min (Y, Z) at max. 1g acceleration. With the attachment head, swivel rates of 15 rpm are possible at angular acceleration rates of 685° / s².

<table>
<thead>
<tr>
<th>Working area</th>
<th></th>
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<tbody>
<tr>
<td>X</td>
<td>4 - 30 m</td>
</tr>
<tr>
<td>Y</td>
<td>1000 - 2600 mm</td>
</tr>
<tr>
<td>Z</td>
<td></td>
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<table>
<thead>
<tr>
<th>Swivel angle</th>
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<tbody>
<tr>
<td>$A_{\text{max}}$</td>
<td>+/- 40°</td>
</tr>
<tr>
<td>$B_{\text{max}}$</td>
<td>+/- 40°</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Max. travel speeds</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>$V_x$</td>
<td>65 m/min</td>
</tr>
<tr>
<td>$V_{y,z}$</td>
<td>50 m/min</td>
</tr>
<tr>
<td>$a_{\text{max}}$</td>
<td>10 m/s²</td>
</tr>
<tr>
<td>$\tau_{\text{max}}$</td>
<td>15 min⁻¹</td>
</tr>
<tr>
<td>$\alpha_{\text{max}}$</td>
<td>685°/s²</td>
</tr>
</tbody>
</table>

Figure 3: 5-axis hybrid kinematics (Source: DS Technologie)

Parallel kinematics for the 5-axis high-performance machining of integrally constructed aircraft components of aluminium

Advantages of the new kinematics

- Faster positioning speed
- Reduction of moved masses (1:3)
- Reduced complexity
- Exclusive use of standard components
- Improved dynamic properties
- Higher rigidity in the swivel axes

Figure 4: High-performance machining with tripod technology
By combining serial and parallel kinematics, it has been possible to distinctly increase performance and availability, with likewise improved rigidity and accuracy (Figure 4). The masses reduced by the machine concept allow higher path feed rates and at the same time greater accuracy. Investment costs are clearly reduced by using standard components for drives and joints. The construction of the tripod head (simple as compared to the angled-axis and fork heads) reduces the costs for maintenance and repair and at the same time guarantees very high machine availability.

2.2. Machine concepts for complete machining

A clear increase in productivity can be achieved with certain applications by integrating deliberately different manufacturing processes in one machine. Integrated machine concepts with a modular structure are therefore an economic alternative for many machine tool customers, who have to link up different machining processes for the machining of one workpiece [4]. If the combination of turning and cutting had largely established itself in turning/cutting centres, machines with further interlinked processes are now coming onto the market. On the basis of selected examples, integrated processes for turning/grinding, turning/cutting and cutting/metal removal by laser are illustrated and also their process advantages described in the following sections.

2.2.1. Process integration for the finish machining of an HSK toolholding fixture

In the manufacture of tool holders with hollow shank cone interface, the highest demands are placed on shape and position tolerances as well as fitting dimensions in order to ensure faultless functioning, also at high speeds, in later use. Such requirements can be met by manufacturing the holders in a turning/grinding centre at minimised machining times.

The HSK blank is finish-machined by the following operations: hard rough-turning, measuring and grinding on one machine (Figure 5). Hard rough-turning of the contour reduces grinding overmeasures so part of the main time required for grinding is saved. Turning and grinding the HSK contour in one holder also cuts times for sparking before the grinding operation and times for handling the workpiece and for retooling and setting up on a separate grinding machine. The machining times (including all machining steps and measuring and clamping operations at 300 – 360 s) depends on the HSK variant. The reduction of the main time compared to conventional production is 50 – 70% [5].

Figure 6 illustrates the machine configuration and shows roughly the machining sequence. The most important machining steps are checking the position of the unmachined part by means of the integrated probe tip, hard rough-turning of the facing attachment and of the tapered shank, external grinding, and measuring of the generated cone geometry in terms of angularity and absolute dimension by a gauge integrated in the machine.
Advantages of process integration
- Production with one retooling operation
- Flexible use of the machine, depending on the HSK size
- Reduced grinding overmeasure, reduced grinding time (internal grinding)
- No zero setting or sparking

Result
- Machining time HSK 63A: 300 s
- Main time reduced by 50-70%, with
  - Improved quality
  - Reduced processing time
  - Reduced material flow

Figure 5: Process integration taking the HSK 63A by way of example
(Source: Index-Werke)

Regrinding of the taper contour is carried out automatically in the event of any dimensional deviation outside the limits of tolerance. The tool-sided part of the interface is machined with the operations hard turning and grinding after the workpiece has been transferred to the counter-spindle.

Changes and variations to the machining steps can be carried out with a low outlay due to the flexible arrangement of tools and machining processes; for example, the set-up time for other HSK sizes amounts to approx. 30 minutes.

Figure 6: Machine design – HSK complete machining (Source: Index-Werke)
If the application changes, the machine can be completely reconfigured, so that its flexible use for other turning and grinding tasks is conceivable. Additional cutting, balancing and laser hardening operations can be integrated into the machine accordingly to requirements.

2.3. Machine concepts for dry machining

The increased costs for wet machining, due in particular to environmental protection requirements, make dry machining an interesting proposition in industrial sectors which manufacture components in large piece numbers. This applies above all to the automotive industry and its suppliers. By changing over to dry machining or minimal-quantity lubrication, new requirements have been placed on production technology and machine design (Figure 7). By dispensing with cooling lubricants, cooling of the workpieces and machine working area during machining is no longer necessary.

Alternative cooling possibilities need to be found, or suitable compensating strategies developed, for filigree and thin-walled parts. Harmful dust may not be released into the environment, and alternative mechanical or physical solutions need to be found for handling dust and chips. For the machine tools, these requirements will affect the design of the working area - with if possible flat and vertical surfaces - as well as complete encapsulation of the machine area in order to avoid contamination of the guide tracks and drive elements and to comply with labour protection requirements. In addition, suitable measures should be provided for removal of the chips that, even given minimal-quantity lubrication, will ensure reliable transport of the chips out of the working area.

**Task areas**
- Implementation of high-speed technology
- Machining of complex components (e.g. clutch housing)

**Problem areas**
- Dust formation/offtake
- Chips handling
- Minimal-quantity lubrication
  - for thread cutting and reaming operations
- Thermal compensation

Figure 7: Requirements for dry machining (Photo: Grob)

A look at the cost structures for the production of cylinder heads in the automotive industry reveals that the costs for cooling lubricants and lubricant conditioning account for approx. 15% of the total production costs (Figure 8). The supply, conditioning and disposal of cooling lubricants, and in particular the disposal of chips with adherent cooling lubricant, account for the greater part of
these costs. Further cost increases are to be expected with the imposition of more stringent environmental requirements, so that the proportion of dry machining and minimal-quantity lubrication will continue to increase in the next years. If only 6% of cutting and drilling operations were carried out on a dry basis in 1999, the automotive industry estimates that this will rise in the next few years to approx. 20%.

**Production of aluminium cylinder heads in the automotive industry**

- **Cylinder head machining (aluminum) in the German automotive industry**

  ![Pie charts showing machining cost distribution](image)

<table>
<thead>
<tr>
<th>Company</th>
<th>Other Machining Costs</th>
<th>Tooling Costs</th>
<th>Cooling Lubricant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>84%</td>
<td>12%</td>
<td>6%</td>
</tr>
<tr>
<td>Company 2</td>
<td>79%</td>
<td>17%</td>
<td>4%</td>
</tr>
<tr>
<td>Company 3</td>
<td>82%</td>
<td>13%</td>
<td>5%</td>
</tr>
</tbody>
</table>

**Development of dry machining in the German automotive industry**

- **1999**
  - Wet: 94%
  - Dry + minimal quantity lubrication: 6%
- **2005 (estimated)**
  - Wet: 80%
  - Dry + minimal quantity lubrication: 20%

![Pie chart showing dry machining development](image)

Figure 8: Costs and share of dry machining in the automotive industry

The disposal of chips from dry machining operations requires additional equipment, since the chips can no longer be removed by way of the cooling lubricant. The basic design characteristic of machine tools for dry machining is the *encapsulated construction of the working area* to prevent escape of microparticles. The machine walls are normally clad with stainless steel sheets and arranged as close to the vertical as possible in the working area. Conveyors in the machine bed (Figure 9) remove the chips by mechanical cleaning methods, compressed-air and suction systems. The mechanical cleaning methods (such as brushes or spraying with dry ice) are only suitable to a limited extent due to maintenance drawbacks and high noise levels. A suitable axis arrangement, typically with a horizontal spindle and horizontal machine bed axis, allows optimum chips fall. Dry machining helps to save costs of approx. 15% (for ABS valve block housing) even though the machining times are above those of the wet process. Other cleaning and conveying systems can be additionally used.

The encapsulated design of the working area also means that an air recirculating system can be used (Figure 10). The air is introduced from above at approx. 4 m/s, flows down the walls of the working area and prevents the chips from coming into contact with the walls. The chips are entailed in the airflow and conveyed through the machine bed into a centrifugal separator. After separation...
of the coarse chips, the pre-cleaned air undergoes secondary cleaning in a lime filter and the fine dust removed. The cleaned airflow is to 90% returned to the working area [8].

**Production of valve blocks**

- Cost savings 15%
- Cutting and feed rates at 30 – 100%
- Machining time approx. 140%
- Surfaces dry partially better

**Figure 9:** Machine design, taking dry valve block production as an example (Source: GROB)

**Figure 10:** The use of an air re-circulating system in the encapsulated design
The coarse chips and the cyclically separated filter contents are discharged into a transport container. An air re-circulation capacity of 4000 m³/h is required (at a working area volume of approx. 1.5 m³) for efficient cleaning. Elaborate measures for explosion protection can be dispensed due to the use of lime filters to bind the dust. Lime (as a low-cost filter material), expenses saved for protection measures, and the costs saved for lubricant conditioning contribute substantially to cutting operating costs as against a comparable wet machining.

3 Systems and components for process-oriented machine tools

3.1. Comparative analysis of drive systems

To be able to implement high-speed cutting (HSC) and high-performance cutting (HPC) it is necessary to choose an appropriate machine concept and in particular the drive system. What counts is not only to attain quickly the required rapid-motion and feed rates by high acceleration rates, but also to maintain the close tolerances when producing complicated contours with small radii and maximum continuous path rates and high path acceleration rates.

Regarding the requirements for feed drives, it can generally be said that there are no particular differences between small to medium size machine tools and large size machine tools. The high static rigidity, high control quality, as well as a low frictional coefficient and high accuracy are required in general (Figure 11) [9]. However there are distinct differences between linear direct drives and electromechanical feed drives with regard to the attainable feed forces, the required connection and cooling capacities and the costs incurred.

Feed drive requirements

- high static rigidity
- high control quality
- low friction
- high accuracy
- low wear

![cover.png](cover.png)

**Figure 11:** Feed drive requirements
3.1.1 Comparison of drives for large-size machine tools

A portal milling machine of gantry construction consisting of Z-slide valve, compound slide rest, crossbeam, columns and bed was used for drive comparison carried out at WZL. In addition to an electromechanical version with electrically biased rack-and-pinion drives in the X and Y axes and ball-and-screw spindle drive in the Z axis, this machine is also available with linear direct drives in all three axes. The electromechanical version has a heavier machine weight, whereby the drives of both machines are so designed that they have approximately the same acceleration rates and speeds.

It turned out that the linear motor requires a distinctly higher connected load and cooling capacity (Figure 12). Nevertheless, the attainable continuous feed forces are clearly below those of the conventional drives. In the linear motor driven variant, the portal milling machine is therefore chiefly suitable for finish-machining, while the conventional variant can also can perform rough-machining operations.

A travel length of 6500 mm was taken as the basis for both drive concepts during the cost comparison of the X-drive. A point worth noting is that the price of the linear motor driven X-axis of the portal milling machine is more than double that of the conventionally driven X axis. The reason is that the secondary parts of the linear motor are more expensive than the rack segments. Also, the additionally required guide shoes (owing to the high starting forces between primary and secondary parts), brake shoes and covers (chips protection) and the higher cooling requirement for the linear motor tend to push up the costs.

The results of the comparison between variant 1 (rack-and-pinion drives - X, Y, ball-and-screw spindle (Z)) and variant 2 (linear direct drives (X, Y, Z)) are shown in Table 1.
For large-size machine tools investment costs for the drive need to be calculated as a factor of the distance travelled contrary to machining centres. The described portal milling machine can be equipped for special applications with an X-axis of 16 m and more. Based on the data of the X-axis, therefore, a comparison of the investment costs as a factor of the traversed distance was also made for both drives systems (Figure 13). The costs of the rack-and-pinion drive are to 100% included for a travel distance of 2 m and the costs of the linear drive were related to this value. For the rack-and-pinion drive, the costs are shown for guide systems and measuring systems and for rack segments as a factor of the distance travelled. For the linear motor, the more expensive secondary parts take the place of the rack segments. By this means we obtain for the linear motor a steeper rise in investment costs over the attained distance traversed.

Finally, the following general statements can be made on the costs of conventional drives and linear motors in large-size machine tools:

- The primary and secondary parts account for approximately half of the total investment costs for a drive unit for the linear direct drive;
- Additional costs arise for the installation of power supply and cooling units due to the higher power consumption of the linear direct drives;
- The higher operating costs for linear direct drives due to higher connected loads and cooling capacities are offset by lower maintenance costs compared to electromechanical drives, because the linear drives operate practically wear-free.
- The primary and secondary parts with associated cooling elements possibly require more space than the electromechanical drives.
- The attainable continuous feed forces are clearly lower in linear motors than in electromechanical drives for comparable acceleration capacities. The linear motor drive requires additional primary parts in order to achieve the same cutting forces in the process as with the rack-and-pinion drive.

<table>
<thead>
<tr>
<th>Table 1: Comparison of drives for large-size machine tools: Technical data [10]</th>
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<tbody>
<tr>
<td>Rack-and-pinion</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Distance traversed [mm]</td>
</tr>
<tr>
<td>Max. speed [m/min]</td>
</tr>
<tr>
<td>Acceleration [m/s²]</td>
</tr>
<tr>
<td>Cont. feed force [kN]</td>
</tr>
<tr>
<td>Cooling capacity [kW]</td>
</tr>
<tr>
<td>Total capacity [kVA]</td>
</tr>
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</table>
3.1.2. **Comparison of drives in machining centres**

In contrast to large-size processing machines, the smaller machining centres often require fast positioning operations and frequent tool changes. Given short distances of travel with high acceleration rates, the use of linear motor technology can make it possible to shorten machining times.

Machining centres mainly use ball-and-screw spindle drives as electromechanical components. Characteristic of machines with ball-screw drive is (even when using direct measuring systems) that a reversal skip is recognisable in the circularity test when the direction of travel is changed that stems from the compliance of the mechanical components. Maximum position deviations are approx. 8 μm. Due to this principle, linear motors have no mechanical flexibility, and positioning accuracy is approx. 1.5 μm (Figure 14). In series, circular milling produced circularity deviations of 2 - 3 μm in the diameter range of 20 - 80 mm.

A comparison of the costs of electromechanical and direct drive systems in machining centres reveals that result additional costs of approx. 20% are incurred for the overall machine when linear direct drives as opposed to ball-and-screw drives are used, whereby the costs for the axes are up to 70% higher.
Cost comparison - drives

<table>
<thead>
<tr>
<th>Costs per machining center</th>
<th>100%</th>
<th>115%</th>
<th>140%</th>
<th>171%</th>
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<tr>
<td>BSD</td>
<td>MC</td>
<td>MC</td>
<td>MC</td>
<td></td>
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<tr>
<td>LDD</td>
<td></td>
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</tbody>
</table>

- Additional costs for the linear motor machine: approx. 20%
- Absolute Position deviation: Linear motor - approx. 1.5 μm
  ball-and-screw drive - approx. 8 μm

Figure 14: Comparison of drives, machine centres (Source: EX-CELL-O, DMG)

An exact comparison and assessment of the two types of drive only makes sense for a specific machining task. Two different workpieces are used as examples to compare the machining times for the production of clutch housings by machining centres with ball-screw spindle drive and with linear motor (see Figure 15). Those machining centres are used for industrial-scale production. Mainly the non-productive times that are positively affected in this example by selecting high-dynamic drives. This is due to frequent tool changing operations and the large number of rapid traverse motions for positioning. The linear direct drives and fast ball-screw spindle drives (i.e. with a high angle of lead) are distinguished by their good acceleration performance [11]. A distinct increase in productivity can be realised by using a multi-spindle machine, as shown in Figure 15.

A further example is a mechanism plate of aluminium produced in few minutes. The positioning operations account for a large part of the total machining time. Using direct linear drives shortens the workpiece production time by 17% – due to higher acceleration values (2g instead of 1g with the ball-and-screw drive) and higher rapid traverse rates (120 m/min instead of 60 m/min with the ball-and-screw drive).

It is clear that the choice of high-dynamic drives will affect positively the positioning times, due to frequent tool changing and the large number of rapid traverse motions that are needed for positioning. A faster and more accurate, but also more expensive drive system is not needed in full scope for every application. However the product being machined must always be included in the
considerations in order to arrive at an economically sound decision [12]. Sometimes importance is attached to significantly shortening the machining time where large piece numbers are concerned (large-scale production), This can be achieved indirectly by using a mullet-spindle machine tool at higher economic efficiency instead of several single-spindle machines with a better individual dynamic performance. Careful and thorough checking should therefore be carried out to establish from the economic and technological viewpoint which drive system is the better one for the machining task in question.

Workpiece: Clutch housing  
Workpiece: Aluminium plate

Figure 15: Comparison of machining times (Source: Grob, DMG)

3.2. Main spindle systems

As mentioned before, the life cycle considerations are becoming increasingly important for machine tools. In addition to costs for repair and maintenance, the costs for repair materials and replacement materials need to be included in order to determine the costs accruing in operation [13].

The example in Figure 16 shows that the material costs of the analysed 3-axis machining centre are made up of:

- 65.6% for the components of the main spindle,
- 13.2% for replacement components such as scrapers on screwed spindles and guide systems
- 8.2% for filter maintenance
- 7.4% for repairs to the tool changing equipment. The rest of the components account for less than 6%.

In this example, the main spindle is the main cost unit. A more detailed analysis therefore includes failure probability, “mean time to repair”, and the life cycle costs per annum. The failure probability and repair time are spread equally over
the components: motor and spindle. The life cycle costs, however, show that with 64.3% the motor and its parts are the main cost originator on failure of spindles.

Figure 16: Comparison of annual repair material costs for machining centres
(Source: Chiron)

The main spindles of machine tools are of special significance since they are increasingly being operated up to their limit of performance. Figure 17 shows the development of main spindles in terms of speed and capacity.

Figure 17: Development of motor spindles for HSC-machining (Source: GMN)
It can be clearly seen that the speed and output of the main spindles could be increased in wide areas in the last ten years. As far back as 1987, a speed of 30 000 rpm was attained with the Sk 40 steep taper tool interface, but only using a very costly injection lubrication system.

Nowadays motor spindles with 80 kW drive power at speeds of 30 000 rpm are used for special applications. It is important to minimise the failure rate of modern spindle units in view of higher machine availability and lower costs for maintenance and repair. Improved transparency of the spindle operating conditions is needed besides identification of a stable cutting process. Typical workpiece defects occur due to spindle oscillation, static and dynamic deformation and also shifts in temperature during machining. Operator errors, inadequate lubrication of the bearings, and critical bearing pre-stressing due to temperatures, speeds and external forces lead to premature spindle failure.

The objective of a project started at the WZL is therefore to increase the availability of machine tool spindles by developing and making an “intelligent” spindle (Figure 18).

**Starting situation**
Little transparency of spindle operating states

**Integration of modules for sensing operating states**

- Workpiece defects due to
  - spindle oscillations
  - static deformations
  - thermal and kinematic shifts

- Spindle failure due to
  - operator error
  - inadequate bearing lubrication
  - critical bearing pre-stressing (temperature, speed, external forces)
  - out-of-balance tools

- Displacement sensors
- Micorodosing systems
- Data storage and transfer
- Leading actuator

Figure 18: Research project „Intelligent spindle units“
Integrated sensor equipment allows the current operating conditions and machining forces to be sensed at all times. Integrating the sensor equipment in spindle components, such as bearing packages provides direct access to information on the locally occurring loads. However, this requires that the sensor equipment be adapted to the variously occurring operating loads, the local ambient conditions, and the energy and signal transmission systems. Integrated actuators allow intervention at all times in the operating state of the spindles in order to optimise the operating conditions [14]. The main benefit of an intelligent spindle unit lies in the monitoring and direct control of the spindle operating state. In addition, valuable information is obtained from data logging allowing conclusions to be drawn about failure causes and enabling changes to be made to the design layout of main spindles.

In respect of the further optimisation of spindle/bearing systems, the objective is being pursued with the development of heavy-duty anti-friction bearings to enable reliable operation right up into the maximum speed ranges. In this connection, the aim is to obtain speed characteristics – defined as the product of speed and average bearing diameter – of $2.5 \times 10^6$ rpm mm with grease lubrication and $3.5 \times 10^6$ rpm mm with oil/air lubrication. Also, a service life of at least 10 000 hours shall be guaranteed.

To realise these aims, research work is being carried out in the fields of “materials”, “coating and lubrication”, “development of new bearing kinematics” and “additional systems for spindles” (Figure 19).

Problem
Maximum speeds reduce service life disproportionately

Objective
To increase speeds and service life

Measures

Figure 19: Research project: improved performance of spindle/bearing systems

In the field of materials, the bearing ring material 100Cr6 used for conventional spindle bearings is to be substituted by materials with an expected higher rating life. The nitrogen-alloyed steel X30CrMoN 15 1 and the surface-layer hardenable steel SAE 9310 are mentioned in this connection [15]. Also the testing of inner
rings made of silicon nitride is planned in order to reduce flaring as a result of the effect of centrifugal forces, and to reduce thermal expansion. The silicon nitride material is also to be used on cylindrical roller and tapered roller bearings. Advantages are expected from the higher compressive strength and the lower density of the bearing bodies and also from the favourable tribological properties of the material combination of steel/ceramics in the rolling contact. The application of hard solid layers on the anti-friction bearing rings shall prolong the lifetime of the bearings by very good wear performance and reduce friction. PVD and PECVD processes are to be used to generate the layers. With the further development of plasma-enhanced processes, coating processes will also be possible at low temperatures, so that structural and dimensional changes in anti-friction bearings can be avoided. With the aid of the PECVD process, undercuts and inner geometries can be coated and the process temperatures kept at room temperature level [16].

In regard to oil feed and the changed tribological conditions, the lubrication of anti-friction bearings is to be optimized in the steel/ceramics contact area. Cylindrical roller bearings will be used for testing whether advantages can be obtained in terms of running performance by way of a modified cage geometry (lubricant pockets) or by changing the location of lubricant feed (e.g. through the outer ring) [17, 18].

In the metal-cutting field, the hollow shank taper tool interface has further increased its lead over taper 7:24 tool interfaces due to its advantages in terms of accuracy, rigidity and suitability for high speeds. In order to ensure reliable and trouble-free operation, the user would welcome more information about the load limits of the interface because of the special design features involved.

![Figure 20: Lift-off moment as a function of the clamping force](image)
A work group at the WZL has in recent years worked out concrete guide variables for use in operation. These are available both as regards the maximum bending moment for various clamping systems and pull-in forces and as regards the tolerable torsional moment where different materials are used.

The limit bending moment passed via the tool lateral force into the tool interface is defined by the unilateral lift-off of the facing surface (Figure 20). As of the critical load moment, the flexibility characteristic curve becomes distinctly steeper, so the connection becomes more flexible. At this point the clamping force is no longer sufficient to maintain full contact between the planar locating face and the spindle nose. The size of this lift-off moment is in decisive measure determined by the pull-in force; the used clamping system and the type of clamping (manual or automatic) have no influence. Thus, the maximum bending moment can also be increased with higher pull-in forces [22]. However, the resultant higher loading of the shank at the clamping incline should not be neglected. This is particularly significant for use at high speeds, since in some clamping systems the clamping force increases as the speed increases due to centrifugal forces acting on the inside gripper segments. Even though this fact increases clamping reliability, it also causes greater loading in the thinnest shank cross-section.

3.3. Damping systems

The working accuracy of a machine tool is determined by the deviations from the set cutting movements occurring at the interface between tool and workpiece. These geometric and kinematics variations are caused by static and dynamic forces which deform all parts located in the flow of power in the machine, such as frames, beds, carriages, spindles, etc. The realisation of a required static rigidity is with good accuracy possible today using modern computation processes in the design stage. As regards the dynamic rigidity of coupled systems, however, many interactions occur which are hard to estimate. In particular, not knowing the damping performance of jointing and coupling surfaces is a major factor of uncertainty in predetermining the dynamic machine properties.

Inadequate static rigidity of a metal-cutting machine will show in the form of shape defects on the workpiece (inadequate dimensional stability). In contrast, unbalanced dynamic properties of a machine will lead to oscillating quantities whose consequences, apart from a poor surface quality of the workpiece and increased machine and tool wear, can be tool breakage and damage to workpiece and machine tool. Against this background, the compliance performance of a machine under dynamic loads is to be regarded as a criterion for its efficiency [25].

3.3.1 Damping elements for spindle/bearing systems

The most compliant element in the power flow of a machine tool is the machine spindle for generating the cutting motion. This applies not only to the static compliance, but also to the dynamic compliance of the spindles. The most
frequently represented bearing principle for spindle bearing arrangements, gearing shafts and also for bearing arrangements with a subordinate requirement profile, is the anti-friction bearing. The main reason for this development lies in the numerous positive properties of these bearings: speed suitability, simple design layout, calculation and choice of standardised bearings, favourable price, and low expenditure for supply units such as lubricating systems. But in the applications where high rigidity and running accuracy at high damping are desired, the spindles with hydrostatic bearing arrangement have the advantage over spindles with anti-friction bearings [26].

Figure 21 shows a combined hydrostatic/anti-friction spindle bearing arrangement. A combination of hydrostatic and anti-friction bearings is used up to a speed of 1200 rpm when the hydrostatic bearing arrangement takes up the radial load and the anti-friction bearings the axial load. From a speed of 1200 rpm up to maximum speed of 3000 rpm, only the anti-friction bearing system is used. For this purpose the oil in the hydrostatic bearings is blown out with air. At high speeds, this avoids frictional heat from being generated in the hydrostatic bearing arrangement.

Drilling machine HS2

**Combined hydrostatic/anti-friction bearing arrangement**
- hydrostatic up to 1200 min⁻¹
- anti-friction bearing up to 3000 min⁻¹

**Advantages:**
- High cutting capacity
- High rigidity and accuracy
- Good damping properties, also with large working radii
- Temperature stabilisation of the spindle box

Figure 21: Hydrostatic/anti-friction spindle bearings
(Source: DS-Technologie)

The advantage of this combined hydrostatic/anti-friction bearing system for spindles consists in the fact that the high rigidity and excellent damping properties of the hydrostatic bearing system are utilised in the low-speed range. For the high-speed range, the largely frictionless rolling bearing system is used.

A poor damping performance of the machine spindles will often cause instabilities in the grinding process as well. In particular when very wide tools are used (for example large-diameter grinding wheels) this will increase the dynamic compliance of the spindle/bearing system especially.

A stable machining process can often only be attained by reducing the metal-cutting capacity [27]. The damping performance of the bearing can be
considerably improved by accommodating the anti-friction bearings in a non-rotating hydrostatic bearing with matched damping action (Figure 22). By this means the outstanding speed suitability of a grinding spindle with anti-friction bearings can be combined with the good damping properties of a hydrostatic bearing system. The basic arrangement is shown by way of a simplified example of a two-mass oscillator. The hydrostatic damping bush is arranged in the flow of power between front bearing and spindle housing. The additionally series-connected bearings increase the static compliance of the spindle system. A significant increase in dynamic rigidity can be achieved given appropriate design layout of the hydrostatics [28].

The test spindle used in the example features an HSK 63 tool interface, in which an added weight of approx. 6.5 kg was inserted. The bearing pockets are supplied with oil by a common pump and pre-throttle valves. Figure 23 shows the compliance frequency response curves of the test spindle in the initial state, without hydrostatic damping ring and with hydrostatic damping ring.

The frequency response of the damped spindle shows that the static compliance increases by approx. 25%, while the dynamic compliance rise however was reduced by a factor of 3. Additionally, the mode of oscillation of the spindle bearing system established with the aid of a modal analysis is shown at the first natural frequency. It can be clearly seen that, besides a purely radial displacement of the spindle at the front bearing point caused by bending of the spindle body, the spindle has also tilted.

The hydrostatic bearing used for this test consists of four radial pockets in one spindle plane. Thus, because of the hydrostatic bearing system, no restoring moment of the spindle tilt can be generated, as would be the case with a double-row radial bearing – shown in Figure 22. A further reduction in radial dislocation at the spindle nose was achieved by resetting the tilt in the area of the front bearing.
3.3.2. Adaptive damping systems

Against the background of the best possible productivity, the requirements increase for maximum speed and also the acceleration capacity of feed axes in metal-cutting machine tools. Implementation of these requirements requires weight-optimised machine components which condition loss of static and dynamic rigidity of the machine and can lead to relatively poor damping properties.

To this day, the dynamic performance of machine tools can in the design phase only be predetermined with limited accuracy even with the help of efficient simulation tools. For that reason, machines frequently exhibit weak points in the prototype stage, which necessitate modification of the structure or use of additional damping systems. Normally, passive auxiliary mass dampers are used to improve the dynamic compliance performance of machine tools. Such systems consist of an accessory mass that is coupled to the machine via spring-damper elements. For reasons of cost, rubber elements are usually used which together with the mass are tuned to a defined natural frequency of the machine. If the system response of the damped system changes, e.g. due to varying workpiece weights or axis travel, the system becomes ineffective. In addition, the damping effect of the accessory system is generally not ideal, because the rubber elements possess a fixed damping coefficient.
In contrast to a conventional auxiliary mass damper, a frictional damper is based not on viscous friction, but on Coulomb friction, which can be set relatively easily by way of the normal frictional force and adapted to the structural properties (Figure 24). Due to the non-linear performance of a frictional damper, however, it is necessary to include the oscillation amplitude of the machine as well as its structural properties when determining the frictional force.

Auxiliary mass damper in the machine tool
- tuning to a defined natural frequency required
- Damping non-adjustable when using rubber elements

Initial state with frictional dampers

Compliance $G$ [Nm / N]

Frequency $f$ [Hz]

Advantages of the frictional damper
Damping easy to set via the normal frictional force

![Figure 24: Use of frictional dampers](image)

If the structural properties and operating conditions of a machine tool are constant in time, a once-only setting of the natural frequency and the normal frictional force will suffice for optimum operation of the damper. The effectiveness of such a system is shown in Figure 25, taking a press as example. The ram is excited by the cutting shock and subsequently executes a dying-out sinusoidal oscillation with the dominant natural frequency of the system. The ram oscillation leads to higher loading of the press-die punch at the peripheral surface when it dips into the press die, which has a negative effect on the tool life.

The dominant natural frequency of the high-speed press is about 150 Hz, while the associated mode of oscillation consists of a relaxation oscillation of the ram. Two eccentrically arranged frictional dampers acting in the vertical direction were used for damping this relaxation oscillation. The natural frequency of the frictional dampers can be adapted to the system by the number of cup springs used. The hydraulic pressure acting on the rear side of the friction linings sets the normal frictional force. The effectiveness of the damping system is illustrated in Figure 25. It is recognised that oscillation of the ram dies out much faster when dampers are used than without dampers. The reduced oscillations practically double tool loading and tool life.
acceleration at approx. 150 Hz (critical frequency) notably reduced
reduction of tool wear (after 100,000 cycles approx. 35 %)

Figure 25: Frictional damper for damping cutting shocks in presses

The system properties of metal-cutting machine tools can additionally change in operation so that the frictional force and the natural frequency of the frictional dampers will need to be adapted in a further development stage. For this purpose, the vibration behaviour is recorded on-line via a seismic accelerograph and analysed as regards frequency and amplitude. The spring stiffness of the absorber mass is set on the basis of the current vibration frequency. The normal friction force is determined from the oscillation amplitude. Optimum tuning of the damping properties to the operating status of the fundamental system is always achieved thanks to the adaptive setting of the damping parameters. The development of such an adaptive system is the subject of current research work.

4. Conclusions

Modern production companies have to respond to shorter product life cycles and rapid changes in product properties with flexible production, high delivery reliability and low production costs. Such qualities are in large part guaranteed by appropriately designed machine tools. Whereas machine tool development in recent years was marked above all by continually higher speed requirements for machines and components, other - in part opposing - machine requirements are now becoming the focus of attention of the user.

A basic precondition for convincing machine tool concepts is that they have to meet process requirements workpiece accuracy, piece numbers and process data determine in large part the required properties of the machine tool. In addition to process-induced machine requirements, the range of services offered by the machine manufacturers is an increasingly important factor for purchasing
decisions. Already today, many machine tool manufacturers offer comprehensive services for operator training, preventive maintenance and machine repurchasing in addition to the actual machine technology, and are thus automatically more integrated in the customer’s overall production process.

Machine concepts, drives and components, as shown by way of the examples, therefore need to be so designed that they will ideally meet the various requirements “flexible and simple, fast and accurate”:

- Flexible through innovative machine concepts and integrated processes,
- simple through machine design and diagnosis
- fast through lightweight construction and co-ordinated drive technology
- accurate through efficient assemblies and components

The requirements make it plain that a machine design that makes good economic and technological sense can only be designed in conformity with the boundary conditions for production processes and production costs, according to the principle: process and costs define machine and components.

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