METHODS FOR REDUCING THERMAL INFLUENCES ON THE ACCURACY OF MACHINE TOOLS

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As the automation of manufacturing process is increasing and because higher machining accuracy is mandatory the disturbance variables influencing the performance of machine tools must be controlled. This paper attempts to give a survey of the present knowledge of the thermal behaviour of machine tools. The effects of thermal disturbances are described and compared with other disturbances. Common methods for the investigation of the thermal behaviour are presented. The methods for reducing thermal disturbances are classified under different topics. Known methods are summarized.

1. Effects of thermal disturbances to the manufacturing process

As the automation of manufacturing processes is increasing and because higher machining accuracy is mandatory the disturbance variables influencing the performance of machine tools must be controlled. Tool wear and thermal deformations are of prime importance since they proceed easily beyond tolerance limits. All known measures for improving machining accuracy summarized in this report are based upon an exact knowledge of the thermal influences on the machining process.

Thermal disturbances are produced by internal heat sources, i. e. elements in the power-flux tied up with dissipation of energy. The amount of dissipation determines the intensity of the heat sources.

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The thermal system "machine-tool" enclosures all heat sources influencing the thermal behaviour, normally also external sources (Fig. 1).

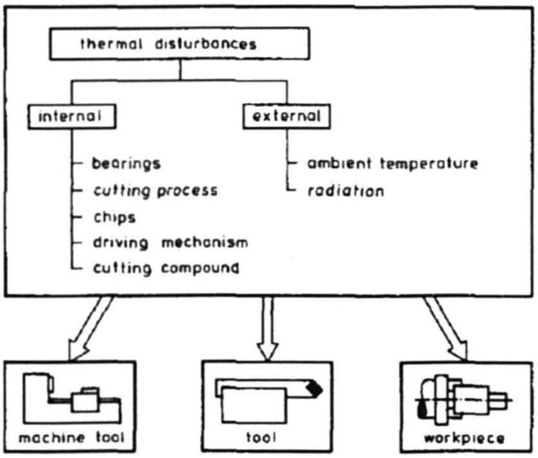

Fig. 1: Thermal disturbances in machine tools

Fig. 2 shows the effects of thermal disturbances, their parameters and characteristics on machine tool, tool and workpiece. The position of tool and workpiece, the guiding accuracy and the action change under thermal effects and cause a decrease of machining accuracy resulting in scrap because of bad surface and proceeding beyond tolerance limits. A classification of the error produced by thermal displacements can be obtained by the dependence of tool position (Fig. 3). The displace-

Effects of thermal disturbances			
	LIMITING QUANTITIES	CHARACTERISTICS	EFFECTS
machine tool	- structure - operating conditions	- big time-constants - low velocity of growth of error	- cutting zone - running behaviour - precision of guides
tool	- material - chucking - geometry - cutting conditions	- small time-constants - high velocity of growth of error - easy to influence	- elongation
workpiece	- material - geometry - cutting conditions	- low velocity of growth of error - difficulties in influencing	- deformation

Fig. 2 Effects of thermal disturbances

ment of the length of overhang of the spindle causes an error independent of tool-position, the straightness error of guide-ways causes an error depending on tool

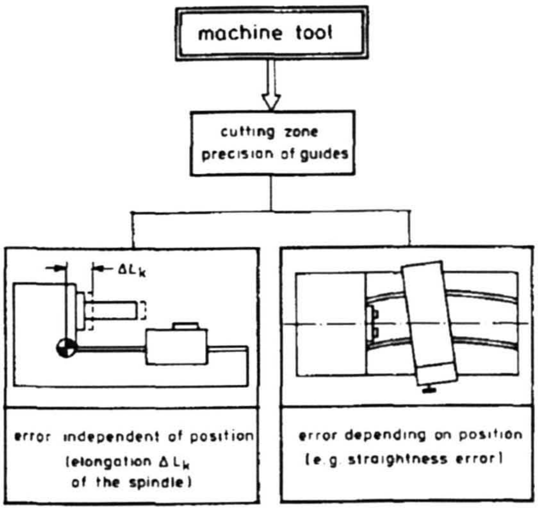

Fig. 3 Error by thermal deformation of machine tool

position. This division indicates limits of compensation methods. Fig. 4 shows the thermal displacements of a milling machine representative to a great number of similar results [1,2,3,4,8].

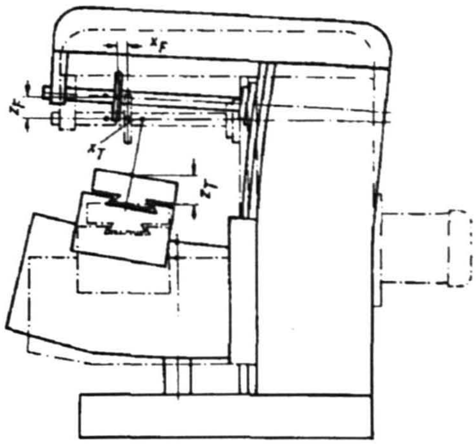

Fig. 4 Thermal displacements of a milling machine [1]

The displacement of guide-ways decreases the straightness-accuracy and flatness. Yokogawa [5]) found, that temperature increase impairs the straightness-accuracy of a grinding machine. Similar results were published about the flatness of planes of machine-tool [4,6]).

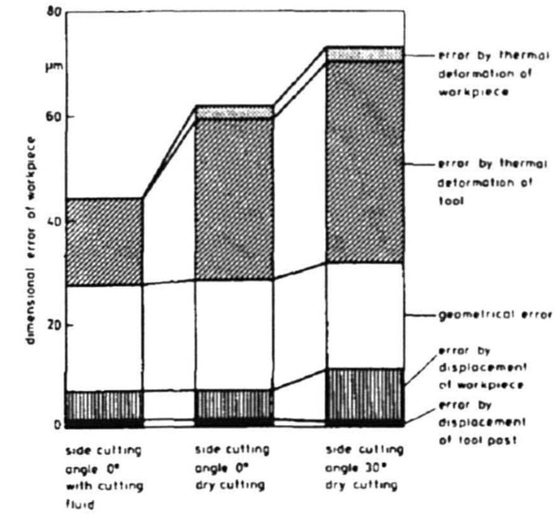

Fig. 5 Percentage of the various errors measured during the cutting process [14])

The clearance of bearings is of special interest because of the great importance to the bearings-power-loss [7,15]). In addition the spindle accuracy is determined by the clearance fixed during mounting. In a point of view bearings and guide-ways represent springs, the characteristics of which influence the dynamic behaviour.

Another important element impairing working accuracy is the tool. The high heat flow, produced during the cutting process, brings about a significant elongation even of short tools. The deformation of the tool is characterized by short time - constants and high velocity of error growth. The cutting compound is of prime importance to the dilatation of the tool[9,10,11,12]).

The portion of the heat produced during the cutting process flows into the workpiece causing an increase of diameter[12,13]). The manufacturing process and its sequence of heavy cuts and finishing is of importance. When a measuring cycle is applied to a warm workpiece during an automatic process it will produce an incorrect diameter. Thermal errors differ from static and dynamic errors in quantity and quality. Sata[14]) separated the total error of a lathed workpiece into error components according to their origins (Fig. 5). The total error caused by thermal influences considerably exceeds the error by static deformation and wear. Dynamic disturbances effect bad surfaces and accelerated wear, i. e. a different quality of error.

The velocity of growth of error charactèrizes thermal displacements. In normal case - exepting the tool - the time-constants average some hours. The sequences of manufacturing, the beginning and duration in an automatic process, is of greater importance to thermal displacements. Fig. 6 [15]) represents the error caused by the point of beginning and the duration of a cutting process. Case A is marked by a small error in the beginning and a high velocity of error growth, case B by opposite influences. The manufacturing system must therefore be thermally stabilized with increasing automation or the error must be compensated.

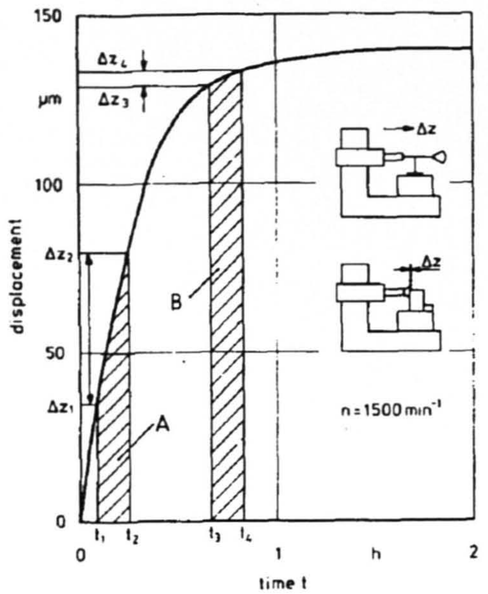

Fig. 6 Influence of the starting time and the duration of the cut on shape and size[15])

2. Methods of investigation of thermal disturbances

The thermal behaviour of machine tools has been investigated experimentally and theoretically in scientific research with the purpose of obtaining a reliable estimation of the size and influence of disturbances. Two basic tasks have to be solved: the thermal behaviour must be presupposed in the planing period to obtain a favourable structure by a calculation of variants. At the end of the manufacturing process the thermal behaviour of prototypes or serial machines must be investigated and improved.

There are two types of analyzing, one involves the machines, the other one uses models. The models used are mathematical-physical and real models. Experimental and analytical methods overlap in the investigation of real models, since the behaviour of the real models must be obtained by measuring techniques.

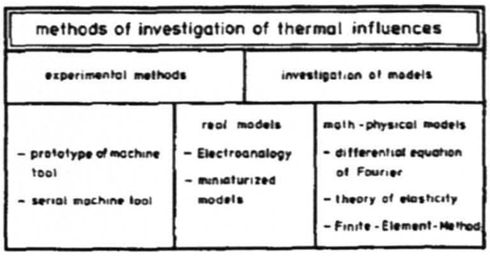

Fig. 7 Methods of investigation of thermal influences

Experimental methods have a major importance. Hypotheses, theories and calculations must be proved to their consistency with reality. Furthermore a great number of input data such as heat conductivity, the amount of dissipation a. o. must be known, before mathematical methods can be used.

Experimental investigations (Fig. 8) lead to the following tasks to be solved corresponding to the chain of thermal deformations. The first element of the chain enclosures the transformation of electrical into mechanical energy. The efficiency of the transformation dictates the amount of dissipation and the coefficient of efficiency is gained by comparing input and output energy.

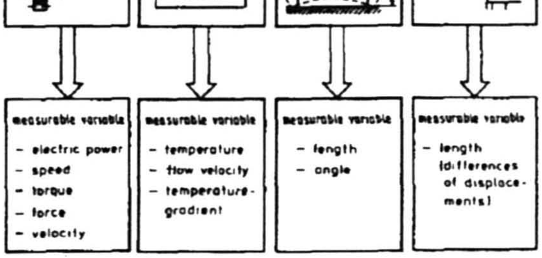

Fig. 8 Experimental methods of thermal investigations

The analysis of power-flux results in efficiency- or Sankey-diagramms. (Fig. 9, 10) [3,4,16]. After solving this first task, information about the location of heat sources is gained.

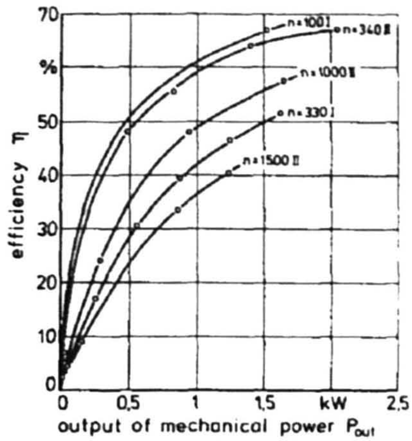

Fig. 9 Efficiency of a machine-tool

The second element of the chain discribes the development of a temperature field in the machine

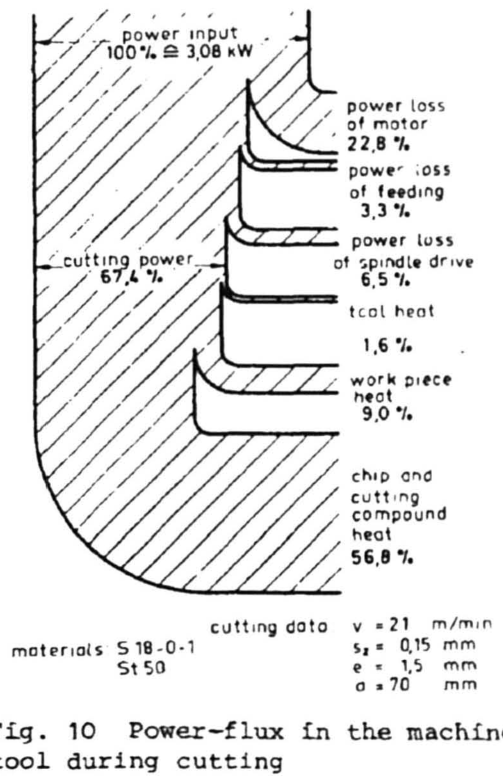

Fig. 10 Power-flux in the machine tool during cutting

tool. The measuring of this temperature field forms the second task. Fig. 11 illustrates a common result with the temperature field of a head-stock [17].

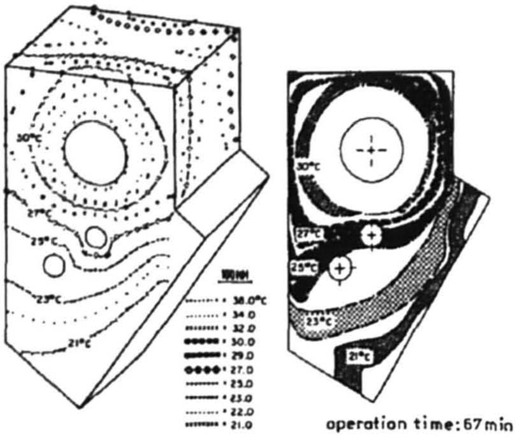

Fig. 11 Temperature field of a head stock [17]

Temperatures can be measured by punctual elements or radiation measuring elements. Thermocouples, semiconductor elements and electrical resistors are successfully and widely accepted. The measuring of radiation depends on a well-known emission coefficient, which also relies on characteristics at the surface. The difficulties in obtaining the emission coefficient prevented the wide use of this method. The relationship of the temperature field with the deformation of a machine tool is given in the theory of elasticity and is determined by the structure and conditions of fixation. Measuring of the temperature field results in only a prediction of displacement tendencies.

The third and fourth element of the chain describes the development of deformations and displacements. The alteration of the positions of tool and workpiece directly impair the working accuracy.
Measuring devices are based on inductivity, capacity, optical and fluidic elements. The holography measures areal displacements by means of interferences. The high expense of devices and the difficulties in fixing the zero point prevent the wide use of this method [2].

A great number of investigations deal with the influence of machine elements and correspond with energy-loss to the thermal behaviour of machine tools [7,18,19]. These investigations resulted in the thermal characteristics of bearings, gears, clutches a. o. (Fig. 12).

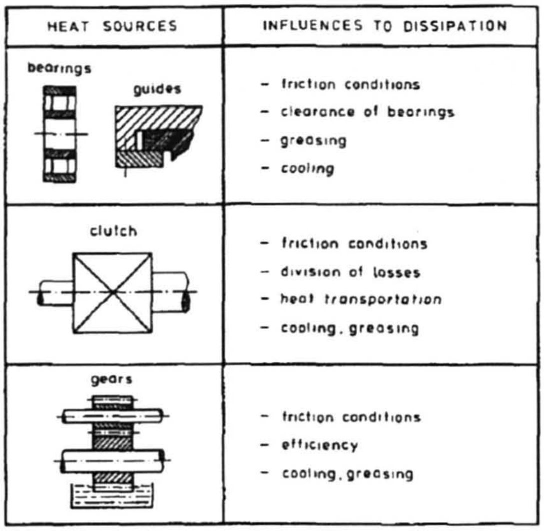

Fig. 12 Influences to the heat production of machine elements

In the past mathematic-physical models and real models were examined and proved to have a great importance in the planing phase of machine tool. The electroanalogy was used to examine real models [20]. This method is based on the analogy between the Fouriers differential equation and the telegraphic equation. The temperature field corresponds to the voltage potential, the heat flow to the electric current, the heat conductivity to the electric resistance and the heat storage capacity to the electric capacity (Fig. 13). However, it is difficult to imitate complicated structures since the production of the model requires much work and the results are quite unprecise. The output of an electroanalogical model is the temperature field.

ELECTROANALOGY		
BASIC LAW	Fouriers equation	telegraph equation
	$\frac{\delta\vartheta}{\delta t} = a \frac{\delta^2\vartheta}{\delta x^2}$	$\frac{\delta U}{\delta t} = \frac{\kappa}{c} \cdot \frac{\delta^2 U}{\delta x^2}$
ANALOGIES	temperature ⟺	voltage
	heat flow ⟺	elect. flow
	thermal conductivity ⟺	spec. elect. resistance
	thermal capacity ⟺	elect. capacity

Fig. 13 Analogies between Fouriers equation and the telegraphic equation

Analytical methods have reached particular significance. The calculation of thermal displacements must be divided into two steps - the calculation of the temperature field and the displacements (Fig. 14) [17,21]).

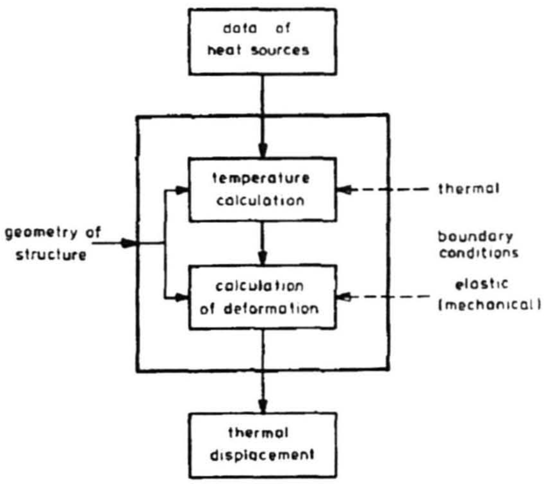

Fig. 14 Structure of the calculation of displacements [17,21])

Calculations based on methods of differences and the Finite-Element Method have been used. In the first case Fouriers differential equation and the differential equations of elasticity have been solved. The first step results in the temperature field of the structure, and this data is the input data for the displacement calculation [17,21]).

The Finite-Element-Methods have overcome methods of differences. Using methods of differences, knowledges of mathematics and of the actual point of calculation is necessary. Furthermore the calculation of deformations is difficult because of the complicated structure of the equations of elasticity.

The use of the Finite-Element-Methods simplifies the temperatures and deformation calculation. This enables a modular computation structure, which helps save computation time and costs (Fig. 15) [21,22,23]).

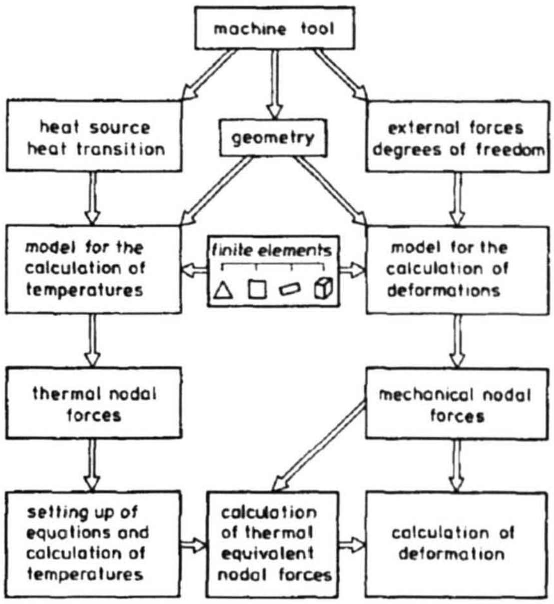

Fig. 15 Sequence of calculation of temperatures and thermal displacements by the Finite-Element-Method [21])

All analytical methods have two main disadvantages: the preparation of input data requires much time and the boundary conditions introduce considerable uncertainty. The first problem can be solved by a mesh generator, which digitalizes the given structure. Therefore only the major dimensions are necessary to compute a result.

The second problem is more difficult to solve. Thermal characteristics, such as energy-loss of machine elements, material properties, values of heat conductivity and heat transmission coefficients must be known and added to the input data. This problem can be solved through the use of experimental investigation in machine elements and the measuring of thermal characteristics. The soft-ware can also be calibrated by comparison of calculated and measured results.

3. Methods of reducing thermal influences

3.1 Classification of methods

The methods of reducing thermal disturbances can be classified by several characteristics. Economic and technical-physical points of view stand in the foreground. The user of machine-tool estimates the relationship between cost and benefit, whereas the producer examines the difference between cost and price (Fig. 16).

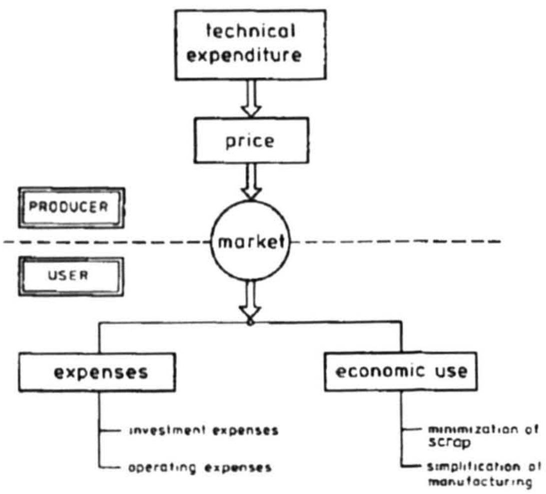

Fig. 16 Economic criteria used to estimate methods of reducing thermal disturbances

The user hopes to save finishing operations and measuring cycles and to obtain less scrap by machine tool with higher accuracy. On the other hand he will examine wether the higher investment expenses and higher operating costs are justified. From this point of view constructive methods are to be preferred to compensation methods. From a technical-physical point of view methods of reducing thermal influences can be divided in those to reduce the margin of error, such as reducing the intensity of heat sources, and those to reduce the effects of disturbances to the working accuracy such as a readjustment of tool (Fig. 17).

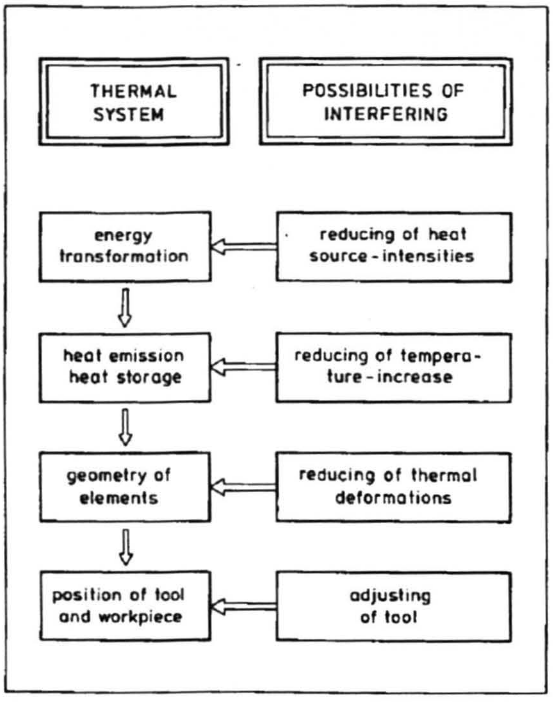

Fig. 17 Methods to reduce thermal effects in a technical point of view

3.2 Constructive methods to reduce thermal disturbances

Constructive methods can be taken into account during the planing period , detailing period and manufacturing of machine tool.

During the planing period the arrangement of the main elements, i. e. the location of heat sources, is fixed (Fig. 18). The disposition of guide ways will exert an influence on the transportation of hot chips. The optimal selection of drive mechanism - electric,

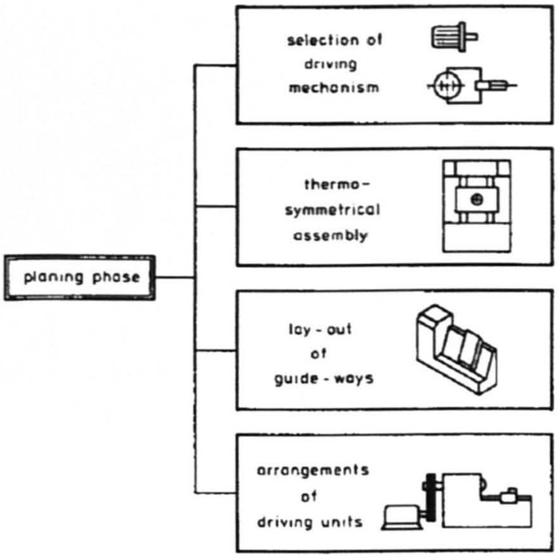

Fig. 18 Consideration of thermal disturbances during the planing phase of machine tool

hydraulic-, can improve the thermal behaviour.

Fig.19[26]) shows, in which way a fundamental decision about the arrangement of main elements effects the temperature field of the structure. The thermosymmetric construction will have lower temperature increase. Also the thermal displacements can be influenced (Fig. 20).

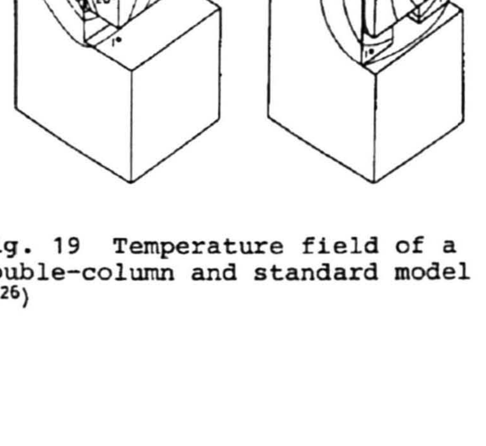

Fig. 19 Temperature field of a double-column and standard model 26)

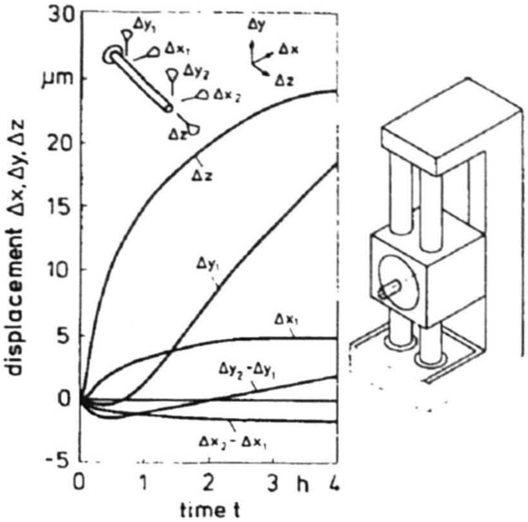

Fig. 20 Displacement of the spindle axis of a double column model

In the detailing phase (Fig. 21) the thermal disturbances can be reduced by optimal bearing arrangements, gear construction, improvement of efficiency (i. e. using roller guides). Furtheron, some special constructive installations can be mounted, such as elongation bars a. o. Typical for a lot of such installations. Fig. 22 shows a device

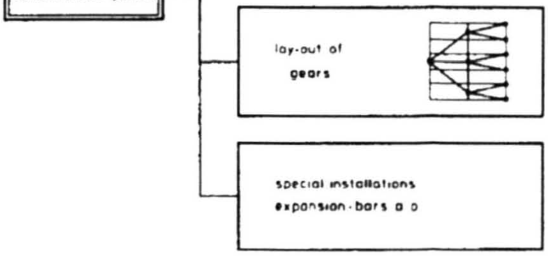

Fig. 21 Consideration of thermal disturbances during the detailing phase of machine tool

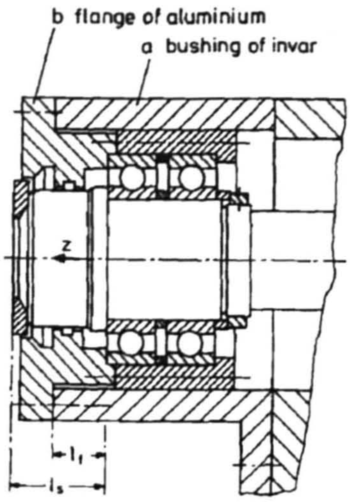

Fig. 22 Installation used to compensate the axial displacement of the main spindle

used to compensate the axial displacement of the spindle (US-Patent 34 29224). The bushing a consists of invar and the flange b is aluminium (elongation coefficient $\alpha = 23 \cdot 10^{-6}\ K^{-1}$). Through an increase in temperature the lenght l_s of the spindle grows and is reduced by the deformation of the length l_f of the flange.

Another method arranges those elements, which determine the accuracy, so that the thermal rigidity R_{th} becomes infinite: $R_{th} \rightarrow \infty$.

This aim can be reached by three methods:

- selection of material with a low coefficient of thermal delatation,
- small length of the element, which will elongate,
- series mounting of opposite deformations.

Selecting a material with low coefficient of thermal delatation the deformation can be reduced in relation to conventional materials even under constant temperature conditions.

A material with a low coefficient of thermal delatation is Invar (Ni - 36).
Although the manufacturing of a machine toOl of invar is not a practical solution, those elements which dominate in the deformation chain, could be produced of invar.

The thermal rigidity can be raised by shortening the length of elements in the deformation chain. The axial bearing on the side of the drive causes a displacement of the chuck in the quantity of spindle deformation. The arrangement of the axial bearing on the side of the chuck reduces the deformed length to the overhang of the spindle.

Also during the mounting phase the thermal disturbances can be influenced. The correct mounting of bearings has an effect on the bearings power-loss (Fig. 23).

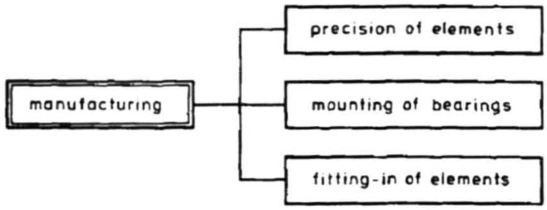

Fig. 23 Influences during the mounting phase to the thermal behaviour.

The accuracy of a machine tool is proved during acceptance examinations. These examinations enclose the measuring of geometrical properties, i. e. flatness, straightness and angles, which easily proceed beyond tolerance limits under thermal disturbances. Therfore the accaptance examinations should enclude measuring cycles after a warming-up period.

3.3 Compensation Methods to reduce thermal disturbances

The effects of thermal influences can be reduced by methods which tend to decrease the origin of disturbances and those which produce opposite effects. The first group encompass those methods which raise the heat emission for example by controlled cooling [25]. Zawistowski [24] first suggested a cooling system for machine tools based on a special double-walled construction. To the second group belong methods which produce a motion of the tool opposite to the relative thermal displacement between cutting tool and workpiece.

Fig. 24 and 25 gives a systematic survey on possibilities to initiate compensation motions of the cutting tool by measuring temperatures, deformations or displacements.

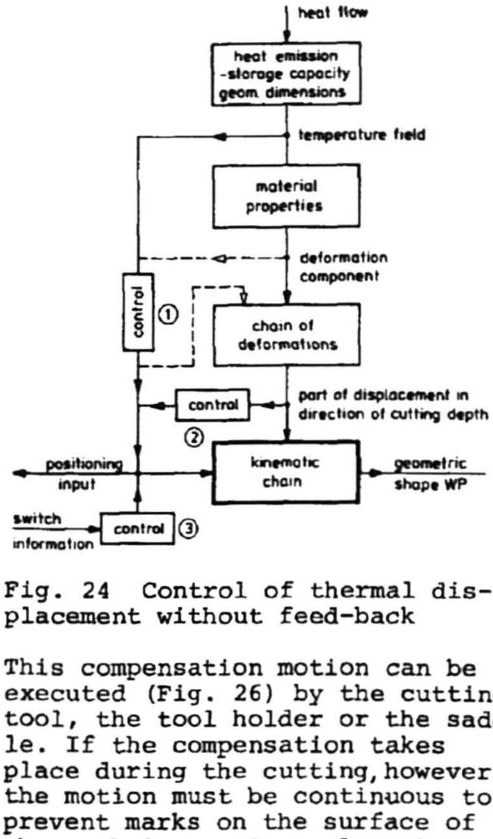

Fig. 24 Control of thermal displacement without feed-back

This compensation motion can be executed (Fig. 26) by the cutting tool, the tool holder or the saddle. If the compensation takes place during the cutting, however the motion must be continuous to prevent marks on the surface of the workpiece. Control systems without feed-back are superiour to those with feed back because of lower technical expenditure. When using systems without feed-back the relation between input and output - for example temperature and displacement - must be well known. Furthermore the difference between the compensation motion and the displacement has to be minute.

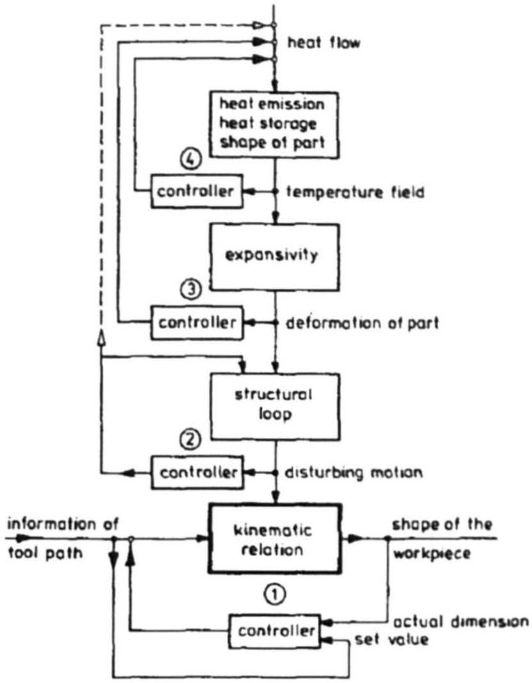

Fig. 25 Control of thermal displacement with feed-back

For higher qualities a feed-back control system must be installed. Control system ① offers the highest accuracy, since the diameter of the workpiece is controlled. But the problem of online measuring of diameters is

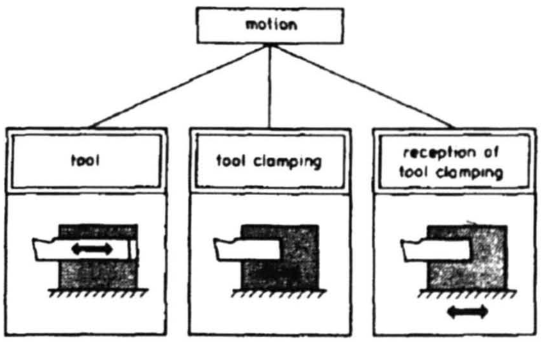

Fig. 26 Possibilities of compensation motions

difficult to solve because of disturbances by the cutting process. The advantages of this system consist of compensation even of other disturbances, such as tool wear, static deformation of guide ways, a. o. The installation and use in automatic production depends on the costs and reliability of these control systems [27,28,29]).
Instead of directly measuring the input data for the control system compensation can be determined through equations or a physical model.

Physical models use the analogy between electrical and thermal conductivity. To copy the behaviour of the machine tool structure with large time-constants-averaging more than two hours - the electrical models need large condensors and resistors. The time-constants of warming up and cooling down of the machine tool are different, however the electrical model has identical time-constants for loading and unloading.

The Finite-Element-Method used as a mathematical model has achieved particular significance [21,26,30]). The behaviour of the real structure is simulated by a model based on a Finite-Element-structure.

The practical application of computation methods is difficult since the location and the intensity of heat sources can generally not be presupposed. The amount of dissipation depends on many parameters which have been investigated in detail for cutting processes, transmissions, couplings, slideways, positioning devices and antifriction bearings. The unsteady variables dissipation and coefficients of thermal conductivity which also depend on operating conditions introduce considerable uncertainty to any computation. Furthermore the method of finite elements does require extensive data preparation and much calculation time, which makes it rather expensive. However, several systems were realized which compensate thermal disturbances based on a control with finite elements [26,30]).

4. Conclusions

All investigations endeavour to improve the thermal behaviour of machine-tools. Control measures with the object to improve machining accuracy can be either done constructively, in this case only a single investment is needed, or by other compensations, which usually cause current operating expenses.

Two different approaches exist:

1) Restriction or elimination of the cause of disturbances (cooling, air conditioning, removal of heat sources, etc.),

2) Error correction by a compensation vector of the same size but opposite direction (for example by numerically controlled carriage movement).

Since the size-control devices are needed for small and medium patch production the conventional size-control equipment without any feedback which is frequently used for mass production is of less importance. The selection of a compensation system of all possible methods is determined by physical and technical parameters, by the initial and operating expenses and by the reliability.

The significant tasks to be solved are the identification and quantification of influences and boundary conditions.

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