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machine tool, cutting process
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PROCESS – MACHINE TOOL THERMAL INTERACTION

Hereby paper shows the structure of mutually connected thermal interactions in a machine tool, a tool and a workpiece, which finally leave their traces on a machined workpiece in form of machining errors. Thermal interactions of a machine tool and the environment on own and workpiece errors were discussed. Thermal interaction cases were considered, connected with the varying environment and the main drive operation, as well as total influence of the varying environment, main drive and two drives of controllable axes. The interactions of the cutting process itself were discussed, assuming three basic mechanisms: thermal, physically-mechanical and tribological. On the example of turning it was proven that the character of changes in total influences between the tool and workpiece has the shape of a temperature curve.

1. INTRODUCTION

Mutual thermal influence of machining processes and the machine itself has a significant influence on the measurement-shape precision of machined elements, and additionally it limits the values of machining parameters and the lifetime of movement units, undergoing significant heating and thermal deformations. Thermal processes taking place as a result of the realisation of machining tasks are very complex, hard to identify by means of an experiment, and to precisely model. The difficulty of identification results from the lack of measurement methods for particular components of the influence (errors) coming from the machine tool, fixing device, tool and the workpiece itself, on which all interactions with mutual connection leave their trace, as well as with the influence of wear – especially tool wear. In order to limit the thermal influence of a machine tool and a process, usually thermal behaviour of a machine tool [1-3] and the cutting process [4-6] are separately improved. This obviously does not lead to the satisfying limitation of the influence of all thermal interactions on the precision of a machined workpiece. Such actions are however indispensable.

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2. GENERAL CHARACTERISTIC OF INTERNAL AND EXTERNAL INTERACTIONS

In case of a machine tool it is burdened in the post-assembly state with an error differing in the entire working area. Such error in the movement conditions, that is during the action of internal heat sources without the influence on the cutting process, changes together with undergoing thermal deformations and displacements, and additionally together with the change of ambient temperature. The machining process generates in a machine tool additional loads and power losses in particular friction nodes, which increase the complexity of thermal loads and deformations. Research centres specialising in thermal research of machine tools can basically identify the above thermal influences on the operational precision of a machine tool, with the accuracy dependent on possessed knowledge and experience. Difficulties escalate with the amount of controllable axes taking part in the realisation of a process.

It is very difficult to accurately take into considerations the influence of chips and cooling-lubricating fluids, because so far there is no method of quantitative assessment, with enough precision, of the amount of transferred heat and the intensiveness of cooling in time, both in relation to the machine tool and to the fixing device, too and the workpiece.

It is the similar case with tools. It is easy to define its deformations caused by forces, much more difficult caused by thermal loads, and very difficult when there is forced cooling acting on it, varying by nature – with variable and poorly defined intensiveness. A commonly used method of increasing the stability of the cooling process is increasing its intensiveness, which considerably boosts the costs of such process.

Changes of thermal loads of a tool generate changes of its deformations, which influence thermal loads changes. Both in case of a machine tool and a tool, internal coupling of loads and deformations from the load distribution and generated heat, as well as mutual couplings take place. Such couplings leave their traces on the machined workpiece in form of dimensional changes proceeding in time. They consist of the influence of the thermal deformation of a workpiece dependent on cutting heat, heat capacity of the workpiece and the intensiveness of cooling. If the cutting process takes place entirely or almost entirely in dry conditions, unstable cooling flow is accordingly lower or can be omitted. A general diagram of internal and external, as well as mutual interactions of a machine tool, a tool and a workpiece is shown on Fig. 1.

Distinguishing and minimising of partial thermal errors can be achieved only by their modelling with the consideration of above described couplings. Only such complex model may enable simulating the generation of a shape-dimensional precision of a workpiece in natural cutting conditions. Such model, because of its enormous complexity, has not yet been created. Stages of generating thermal errors in a system: machine tool – workpiece – tool and the appearing interactions are shown on Fig. 2.

At the same time, it is an integrated model of thermal interactions of deformations, which leave their trace in a complex manner on a machined workpiece. It is worthwhile to introduce such thermal errors, which can be currently measured and described by means of models.

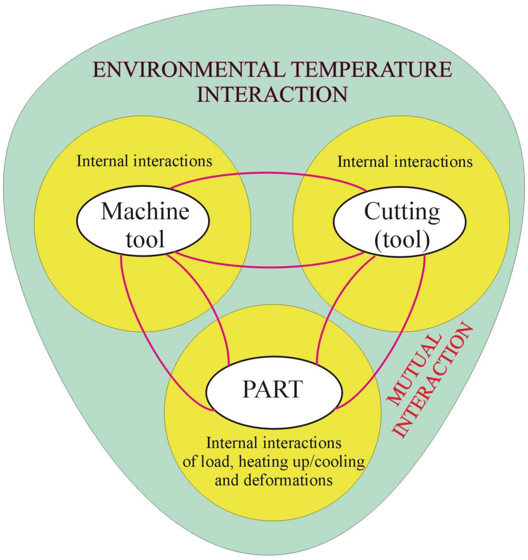

Fig.1. Scheme of internal, mutual and environmental interactions of load, heating up, and deformations on final PART machining error thermally induced

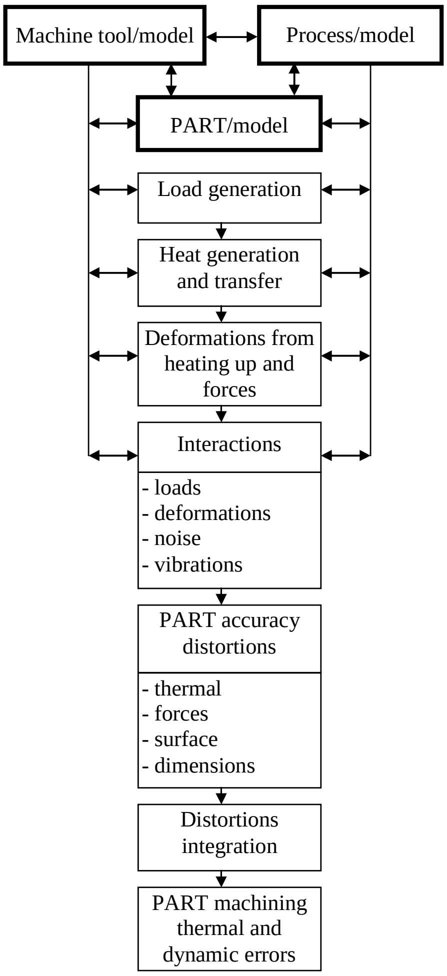

Fig. 2. Machine tool, process and part interaction on machining thermal errors – model components

3. THERMAL INTERNAL AND ENVIRONMENTAL INTERACTIONS IN A MACHINE TOOL

The precision of a machine tool in operational conditions depends on the series of internal and external interactions, as well as the interactions between them. The interactions take place between:

- operational conditions of a machine tool (rotational speed of a spindle, ambient temperature, etc.),
- power losses in particular elements of a kinematic system,
- temperatures,
- thermal displacements of a machine tool.

Power losses are a function of operational conditions and depend on the constructional properties, geometrical and mechatronic structure, material properties of particular elements and units, lubricating method, method and intensiveness of cooling, etc. Power losses cause variable in time temperature distributions, which by influencing e.g. internal load of bearings, viscosity of the lubricating agent, coefficients of heat absorption on machine tool surfaces, secondarily influence the magnitude of power losses. As a result of mutual couplings between all of these factors, a complex dynamic thermal state of a machine tool is created, characterised by continually undergoing changes of power losses, temperatures and thermal displacements in time (Fig. 3).

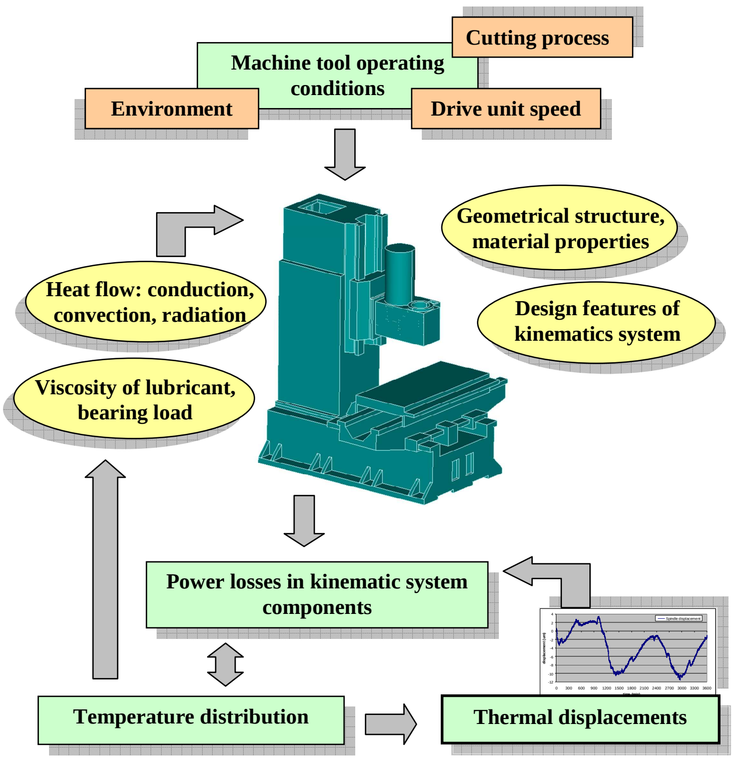

Fig. 3. Interactions between internal and external interactions in a machine tool

Machined workpiece error depends, among other things, on the amplitude of such changes. Such amplitude is influences mainly by the changes of spindle rotational speed during operation time of the machine tool. Additionally, the influence of ambient temperature changes shall not be omitted.

The influence of ambient temperature on thermal displacement changes and simultaneously on machined workpiece error can be in certain conditions very significant. It is clearly visible in case depicted on Fig. 4. Ambient temperature changes in a production hall in the range of 5ºC during 20 hours were accompanied by the change of axial displacements of a spindle in a non-operating machine tool in range of ca. 16 μm. This constituted as much as 15% of maximal axial thermal displacements of a spindle appearing during operation of this machine tool.

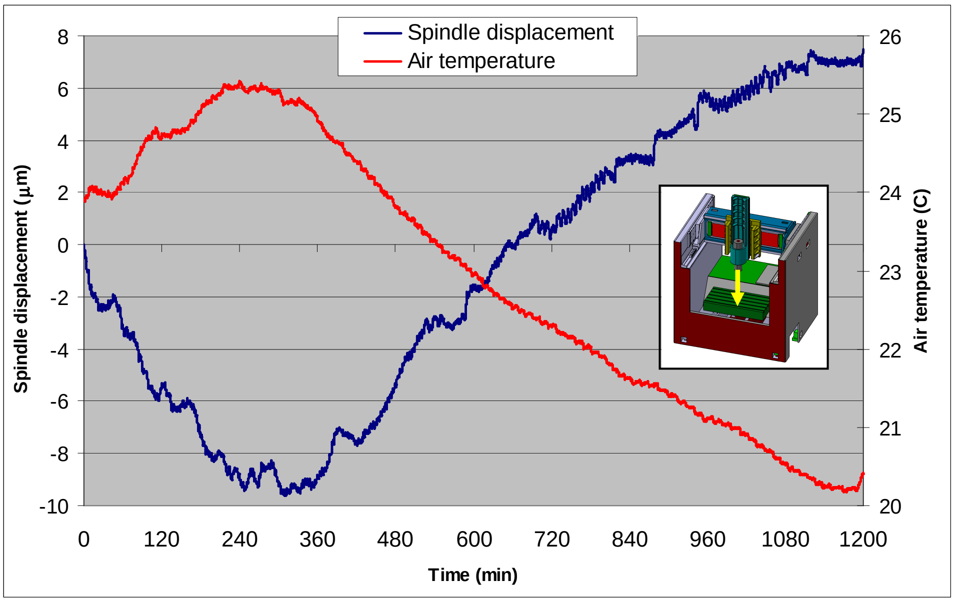

Fig. 4. The influence of ambient temperature changes on changes of axial thermal displacements of a spindle in a non-operating machine tool during 20 hours

The influence of rotational speed changes on thermal displacement changes of a spindle tip in the conditions of a long-lasting operation of a machine tool with maximum rotational speed of 45.000 rpm is shown on Fig. 5. Additionally, the influence of ambient temperature changes was also taken into consideration (red line on Fig. 5).

The example shown on Fig. 5 applies to the 18-hour working cycle on idle run in conditions possibly closest to real-life operating conditions, during which the rotational speed of a spindle was changing every 30 min, while ambient temperature was changing in the range of 4ºC. Operating cycle consisted of three identical sequences. Every one of them lasted 6 hours. (operating cycle parameters, see upper part of a Fig. 5).

Rotational speed changes very heavily influence the changes of thermal displacements and simultaneously the error of a machined workpiece, especially during large speed changes. In case of the change in rotational speed from 45.000 rpm to 18.000 rpm (240 min) the displacement of a spindle tip quickly, during merely few minutes, decreased from 100 µm to ca. 30 µm, which may leave traces on a machined workpiece, deteriorating its shape-dimension precision.

On Fig. 5 one can also notice the influence of ambient temperature, which overlaps with the interaction caused by the changes of spindle rotational speed. Together with the decrease of ambient temperature from 23,5ºC (160 min) to 19,5ºC (1080 min) a tendency is visible, in form of shifting thermal displacements in the direction of lower values, with a constant range of displacement changes. Such tendency is depicted by 2 blue dashed lines on Fig. 5.

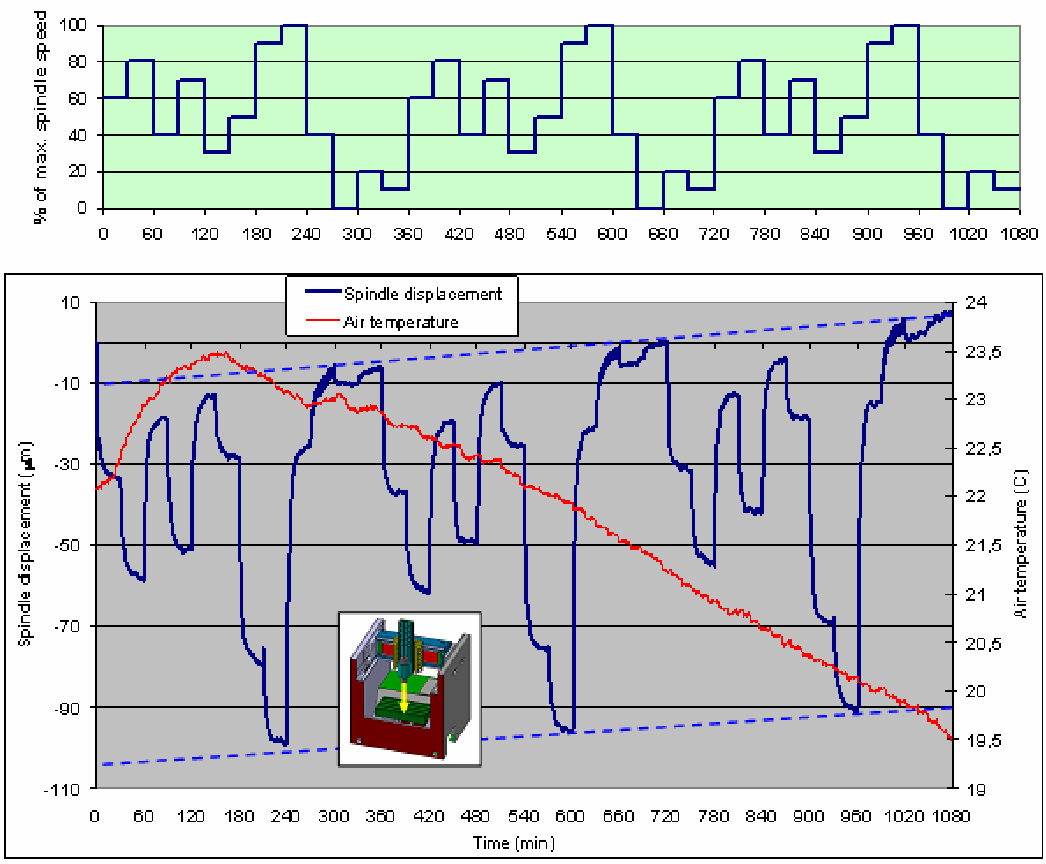

Fig. 5. Changes of spindle thermal displacements in period of 18 hours with rotational speed of a spindle changed every 30 min and ambient temperature varying in the range of 4° (max. rotational speed of a spindle – 45.000 rpm)

Changes of rotational speed of a spindle and ambient temperature in time of machine tool operation have a large influence on changes of thermal displacements of a spindle tip and simultaneously on machined workpiece error. They can be the cause of large difficulties during the assurance of a required precision. Because of this fact, it is very often required to use extremely precise methods of compensating thermal displacements, based on very precise models, which must take into consideration couplings taking place between internal and external interactions.

The intensiveness of spindle tip displacement changes is highest during first minutes after changing spindle rotational speed. This is illustrated by Fig. 6, which shows a fragment of a cycle from Fig. 5 covering a period between 530 and 630 min. In this time the rotational speed of a spindle changed three times: from 22.500 to 40.500 rpm, from 40.500 to 45.000 rpm and from 45.000 to 18.000 rpm. During 30 minutes after the change of rotational speed from 22.500 to 40.500 rpm, the displacement of a spindle tip increased by 50 μm (from 25 μm to 75 μm) - the change of displacements was largest during first 5 minutes, and equalled 43 μm, which consisted as much as 86% of the entire range of displacement changes. During 30 minutes after the change in rotational speed from 45.000 to 18.000 rpm the displacement of a spindle tip decreased by 75 μm (from 95 μm to 20 μm) - the change of displacements during first 5 minutes equalled 58 μm (77%).

Large changes of spindle tip displacements during first 5 minutes after the change of spindle rotational speed can leave traces directly on a machined workpiece. Therefore in this period of time an especially precise displacement compensation, realised in the intervals of few seconds, is required.

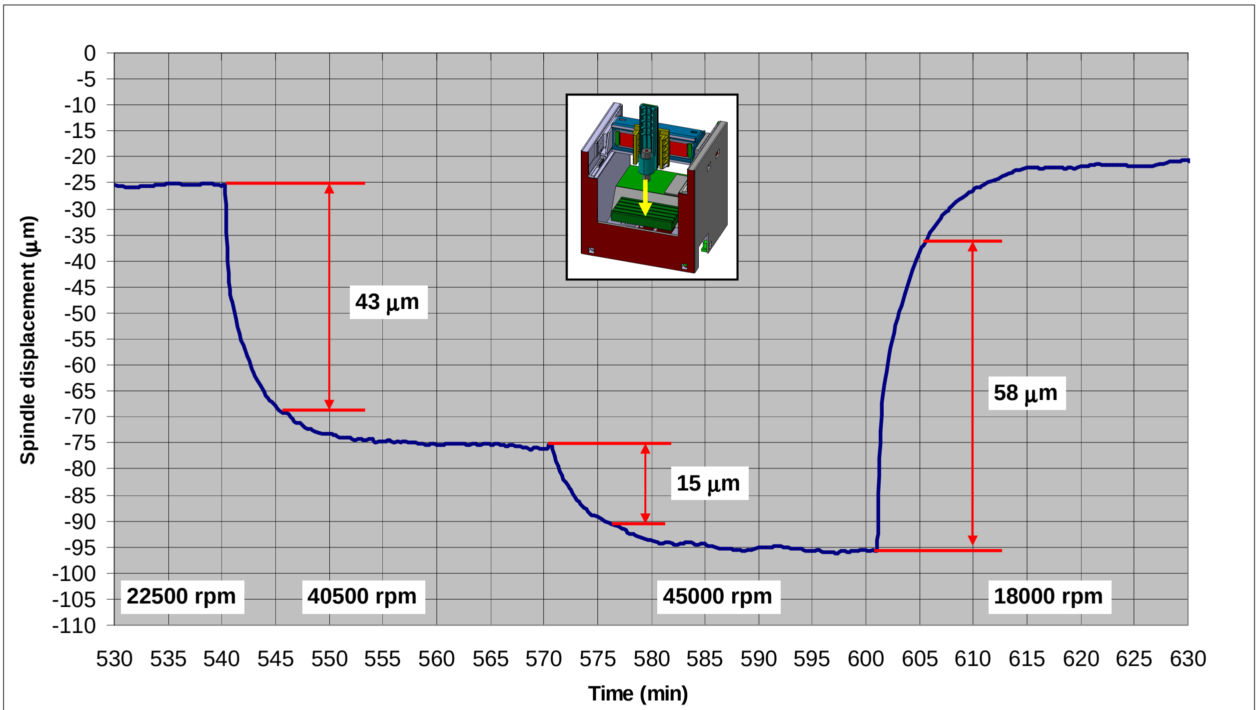

Fig. 6. Intensiveness of displacement changes after the change of spindle rotational speed

The problem of mutual thermal interactions becomes even more complicated, when thermal elongations of one group of units, decisive about the resulting thermal error of a machine tool, sum up while the others compensate the interactions of the first group. Such situation takes place e.g. in a lathe, in which the direction of thermal displacements of a spindle causes the workpiece to move away from the tool, while thermal expansiveness of a tool head and the cutting tool itself causes the tool to approach the workpiece. Additionally, thermal elongations of a working ball screw, especially in the X direction, cause the tool to significantly move away from the workpiece. The resulting change of a relative tool-workpiece position (thermal error) achieved during the multi-hour measurement is shown on Fig. 7.

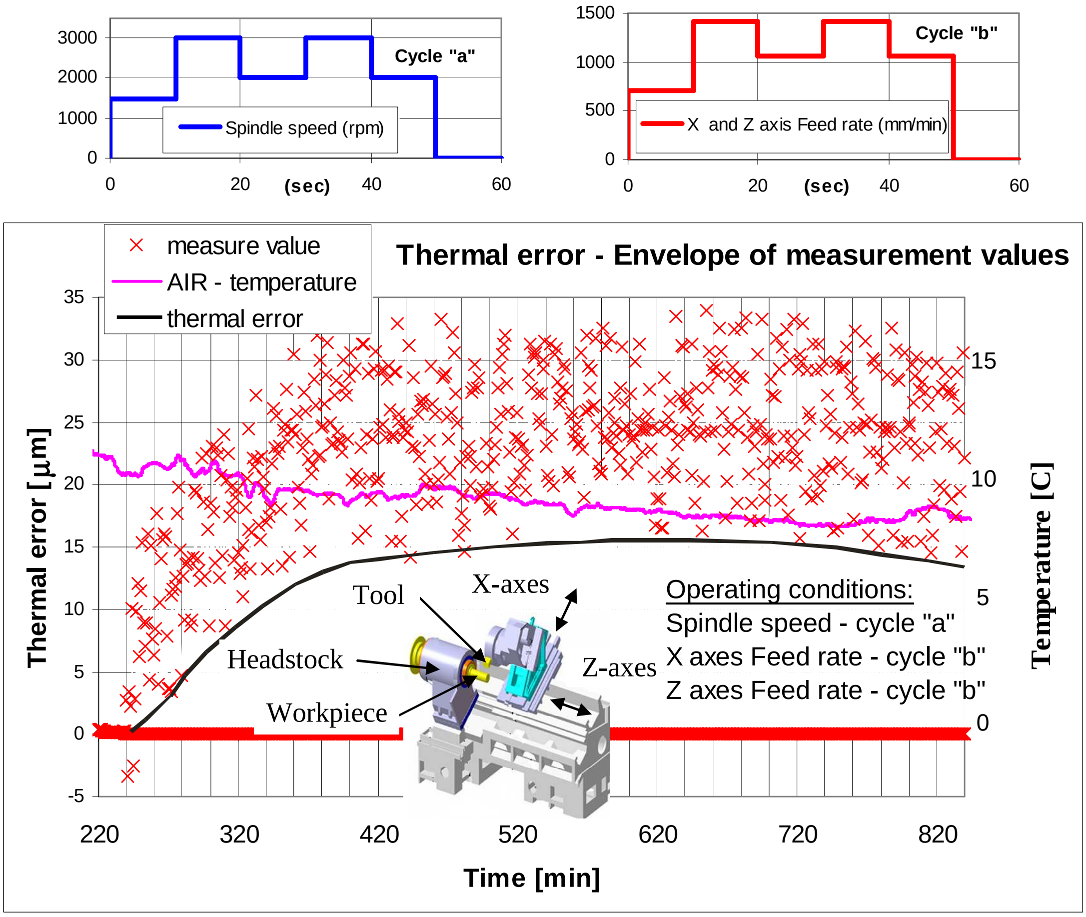

Fig. 7. Combined thermal influences of a spindle drive, drives of X, Y and Z axes and ambient temperature on thermal error of a machine tool, measured as the change of a relative tool-workpiece location during the realisation of predefined drive working cycles

A line of thermal error in this case is determined by the envelope of all extreme values of the measurements of the distance between a moving tool and a spinning workpiece. The summary thermal error was composed of the interactions of heat sources connected with the spindle drive and the drives of controllable axes X and Z. 60-second working cycles of a spindle and feed drives, repeated throughout the measurement period, are in a simplified form shown on Fig. 7. Measurement points represent situations, when the tool should return to the initial position. However, due to large dynamics of movements, even a large sampling frequency could not assure that the moments of the maximal approach of a tool to the workpiece can be captured. Measured extreme values are therefore the closest to the expected values of a thermal error.

In order to make it possible to model such resulting thermal error, as the one achieved in measurements, it is not enough only to model the efficiencies of internal heat sources, such as motors, bearings or ball screws, and take into considerations the directions of thermal elongations. Because in a complex state of thermal interactions, the delay of the reaction of certain units on temperature changes in other units or in the environment, can be of a large importance. Such delays (Fig. 8) are also observed in a lathe, during almost 3-day long operation of a headstock according to the “a” cycle from Fig. 7. The temperatures of a headstock and a ball screw in the X axis were influenced by heat sources connected with the spindle drive and twenty-four hour ambient temperature changes. A headstock was almost a constant heat source, while the role of the excitation generating machine tool temperature changes was played by the ambient temperature. It appears from the figure that the periodical cycle of headstock and ball screw temperature changes is indeed the same and equals, same as for the ambient temperature, 24 hours, but these interactions are shifted in time relatively to each other. This undoubtedly is connected with the isolative action of the covers of a screw transmission. Such shifts must be also taken into considerations during the definition of the balance of thermal elongations, making up the thermal error of a machine tool.

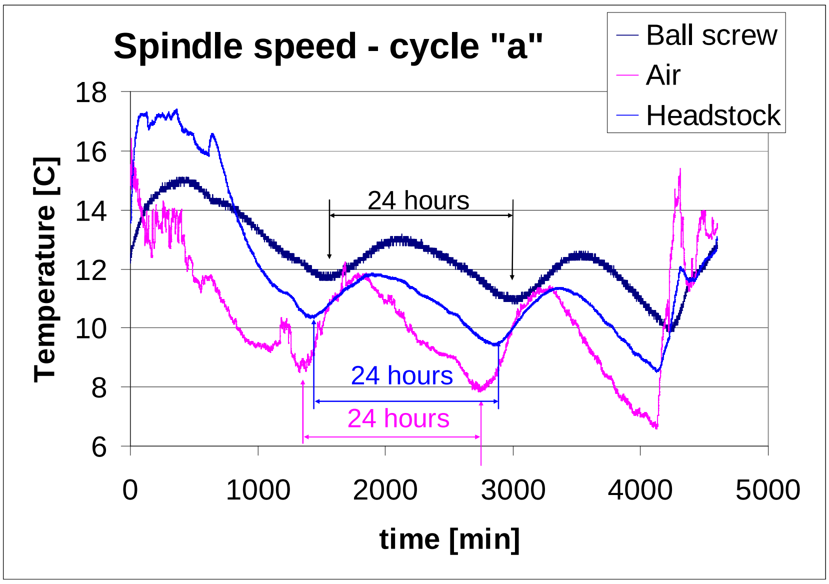

Fig. 8. Interaction of long-lasting ambient temperature changes on the temperature of the units of a lathe, operating according to the cycle “a”

4. PROCESS INTERACTION

The cutting process is the important source of interactions on the final effect of shaping, understood as the technological quality of machining and the reliability of a process, which is especially important in automated, high-productive manufacturing. In a structural model of cutting, the physical mechanism of the cutting process influences, in direct or indirect manner, the shape-dimension precision of the workpiece, machined surface quality, strength, durability and reliability of a tool, as well as energy consumption, efficiency and effectiveness (productivity) of machining [7,8].

The interaction of the cutting process itself can be discussed by assuming three basic mechanisms: physically-mechanical, thermal and chemical [9]. They make up the *unit event* (shown on Fig. 9), characteristic for a given method and a manner of cutting. In the presented diagram of process interactions the combined effect, which is a sum of component phenomena with different intensiveness, influences, through all components of the machine tool – device – process – tool (mdpt) system, the state of a technological surface layer, that is the geometrical structure of a surface and the physical/mechanical state of the sub-surface layer.

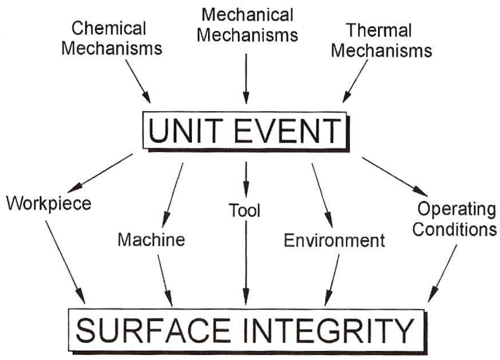

Fig. 9. Influences on the unit event and surface integrity (optionally also part accuracy and its thermal distortion) [9]

Thermal interactions including heat sources and heat fluxes. The classic model of heat sources and heat propagation in the cutting zone between the machined workpiece (1), chip (2) and tool is illustrated by Fig. 10a. In the model, frictional (flux q_f) and deformational (flux q_d) heat sources were taken into consideration. After the introduction of the heat dispersion coefficient *R*, heat flux resulting from the chip equals to Rq_d, and to the surface layer of the workpiece ca. $(1-R)q_d$.

a) b)

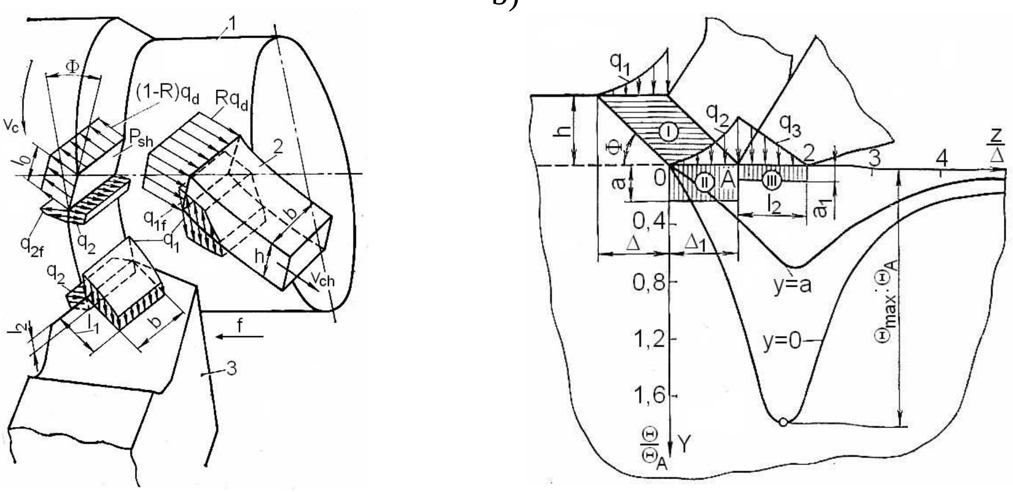

Fig. 10 Localization of heat sources and heat fluxes (a) and complex spatial heat source in the subsurface layer of the workpiece (b) in turning after Reznikov [10]. 1-workpiece, 2-chip, 3-tool, Psh-shear plane

On Fig. 10b, a model of the temperature distribution in the contact zone of the tool with the machined surface is shown, assuming that the complex, total cutting heat flux is composed, after approximation, of parts I, II and III with the intensiveness of, accordingly, q_1, q_2 and q_3. Additionally, a dimensionless temperature was introduced on the Y axis, i.e. the ration of a local temperature Θ to the temperature in proximity to the cutting edge Θs.

Mechanical interactions including forces and contact stresses. The geometrical decomposition of the total cutting force on components Fc, Fx and Fp is commonly known [7]. In a precise analysis, also forces acting in the contact area between the flankface of a tool and a machined surface should be considered, which is more justified when the tool undergoes wearing during the process. Fig. 11 shows the classic mode of the distribution of normal and shear stresses in the chip-tool contact zone, proposed by Zorev.

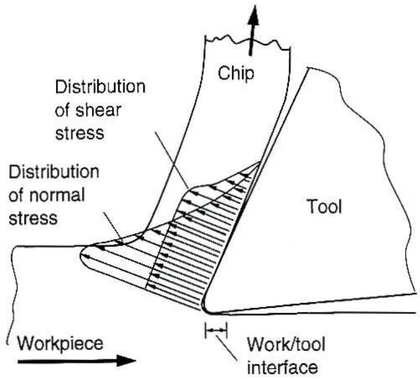

Fig. 11. Tool stress distributions in the chip-tool interface

Tribological interactions including different tool wear mechanisms -tool wear mechanisms and tool damage. In the cutting process, a very complex tool wear mechanism occurs, which usually applies to functional surfaces as on Fig. 12. The effects of geometrical changes of a tool caused by wear are shown on Fig. 12b. It should be added that tool wear is a factor which in a large degree influences the shape-dimension precision and the surface quality.

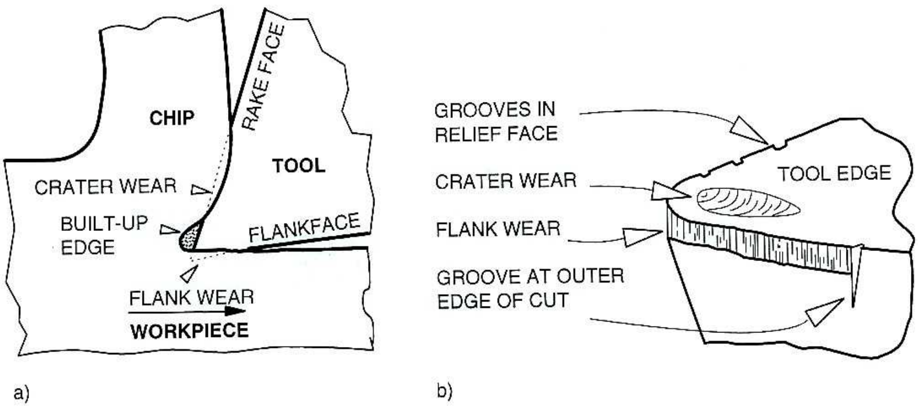

Fig. 12. Typical location of tribological effects and wear failure on the tool

Typical sources of part distortions in machining. Regardless of the character and the course of machining, a tendency of the appearance of distortions from assumed dimensions, shape and surface quality of a workpiece must be dealt with. In many cases, inaccuracies are generated due to the removal of residual stresses remaining in semi-finished products or introducing new stresses during the process. Fig. 13 is a comparison of the deformations in a sample according to the AST standard, caused by stresses in the processes of abrasive machining (grinding of surfaces) and chip machining (milling of surfaces), appearing with the varying intensiveness of mechanical and thermal interactions. It is clearly seen that the deformations in these two variants of machining have opposite signs, i.e. stretching dominates after grinding, while compression dominates after milling.

When it comes to the interaction of a mechanical manner, they lead to the strengthening of the surface layer material, which measure can also be the stored energy [11]. It has been proven that the value of such energy is closely connected to the elastic displacements of machined parts, which cause shape and position errors, such as the displacement of the thin-walled sleeve's axis. Because of this fact, controlling the stored energy can be one of the methods for controlling the process in the area of shape-dimension precision, especially in a precise manufacturing.

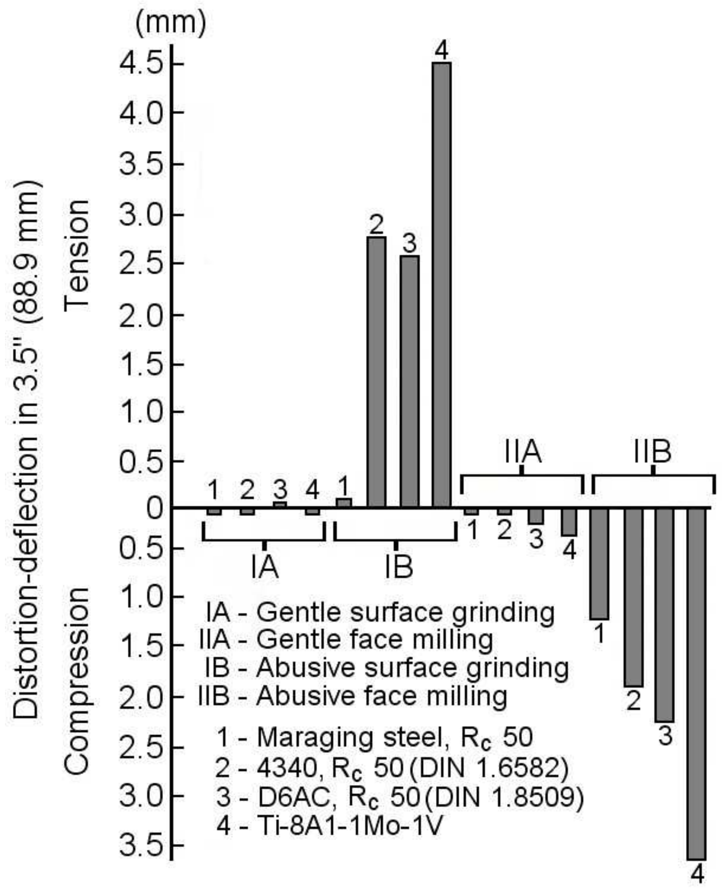

Fig. 13. Deformations of a sample subjected to grinding and milling [12]

5. PART INTERACTIONS

Case study-hard machining. Fig. 14 shows possible sources of machining errors, appearing in dry machining of hardened materials. Emitted heat is the cause of workpiece thermal deformations and changes in the microstructure of the surface layer (creation of a characteristic white layer).

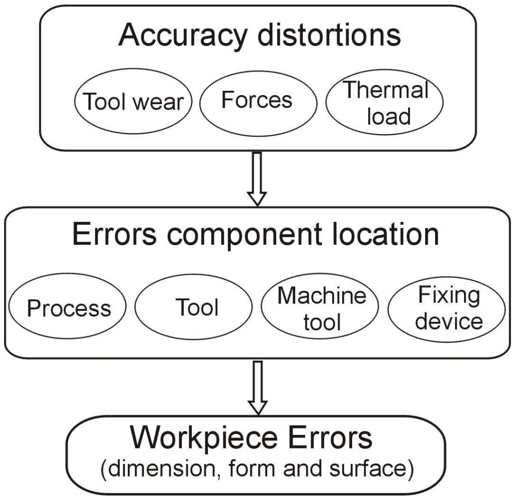

Fig. 14. Major error drive factor and error sources in precision hard turning

Now, the achievable dimensional accuracy in precision hard turning using CNC machine tools with high static and dynamic stiffness, thermal stability and high precision motion control is ISO IT5[12]. As shown in Fig. 14 many factors affect the part accuracy and process stability and reliability. Three main factors, namely tool wear, cutting forces and cutting thermal load are the driving factors providing the error sources in process, tooling, machine structure and fixing device. For instance when flank wear of CBN tool reaches the value of VB=0.2 mm the dimensional errors on 100Cr6 (60-62 HRC) steel parts measured in radial/axial directions increases up to 25 µm. Moreover, because the cutting temperature is at least 800^0C substantial thermal expansions of both tool shaft and the workpiece are observed. It is assumed that the thermal effects can contribute to more than 50% of overall error of the machined parts. In particular, for the same machining conditions (v_c=160 m/min, f=0.05 mm/rev, ap=0.05 mm) thermal expansion on the CBN tool tip and workpiece can reach up to 10 and 15 µm, respectively [12]. In order to minimize possible errors in precision hard turning active error compensation and special monitoring systems are proposed.

The machined part is subject to the influences of cutting forces, which cause deformations dependent on its stiffness. In many cases, flexible elements must be supported in many places, in order to assure that shape errors after machining do not exceed permissible values. It can also be subject to deformations due to the alignment and fixing process in a device. The prevention of such deformations requires the assurance that boundary values of forces are not exceeded, because of the required precision, which is most reliably achieved by an adequate automation of alignment and fixing, with automatic monitoring of forces and deformations.

It is much more difficult to limit the thermal interactions connected to ambient temperature changes and the heat created in the cutting process. The counteraction to thermal deformations in practice is based on adequately intensive cooling of the cutting zone, by means of a cooling-lubricating fluid. This solution is disadvantageous ecologically and economically because of the complex process of distribution and to supply the fluid to the cutting zone, which is circulating in a closed circuit and the separation of chips. Therefore, whenever possible, dry cutting or minimally fluid-cooled cutting is aimed at.

During dry-cutting, these elements taking part in the cutting process heat up intensively, which have a small thermal capacitance and are under the influence of heat sources with high yield. A tool tip and a workpiece are subject to strong local thermal deformations. The influence of such deformations is hard to identify, as well as to model. On a cylindrical part, for example, dry-turned, such deformations are reproduced in form of the change of its outline. The character of such changes, connected to the summary thermal elongation of a tool and the thermal change of the part's diameter, is consistent with the shape of a temperature curve (Fig. 15) [13]. On All presented graphs, a distinct stabilisation of the overlapping thermal deformations is visible, connected with the thermal capacitance of a tool, chips and a workpiece, as well as the intensiveness of heat transfer to the environment.

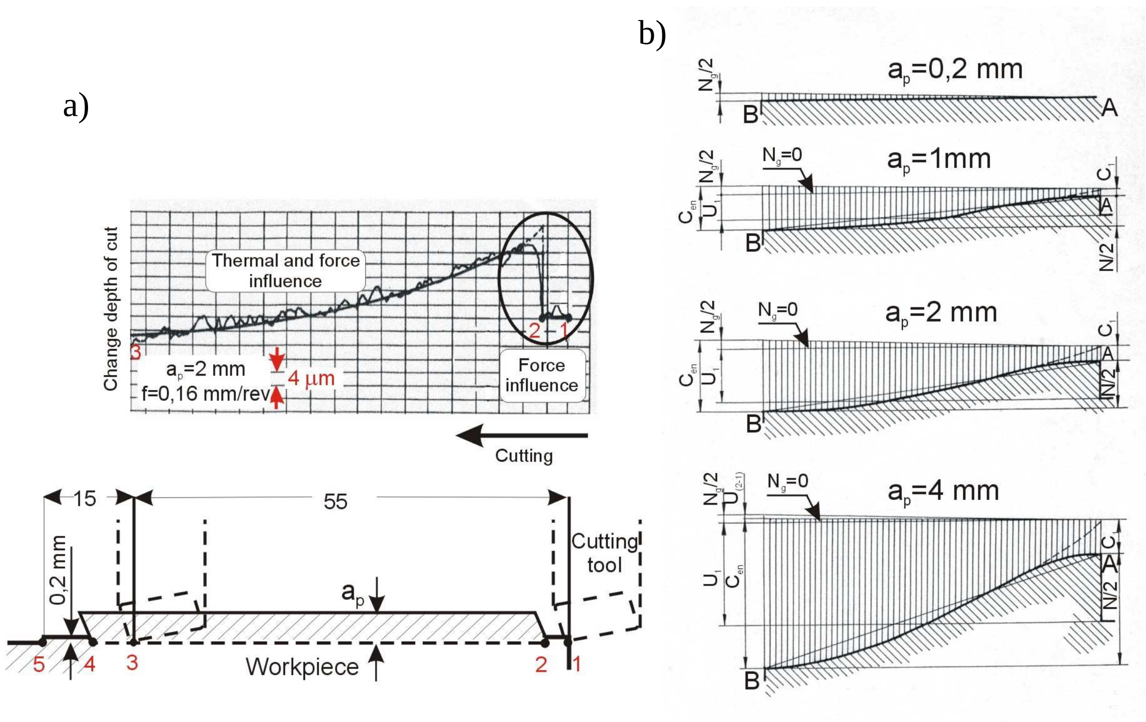

Fig. 15. Interactions between the workpiece and the tool in the cutting process: a) example of a profilogram of the surface outline after turning, b) influence of cutting depth on machining thermal error C_{en}.

After the start of cutting, during the cutting-in of a tool into the machined material, appearing thermal deformations grow slowly and cause distinct flattening of the part outline. In the further phase of cutting, the curve of summary deformations takes the typical shape of a temperature curve. Its changes, omitting the preliminary cutting-in phase, depict mainly the machining error C_{en} connected with thermal phenomena. The larger amount of heat generated in the cutting process, the more intensive run of a curve of summary deformations. It is visible on the graphs from Fig. 15b, obtained with different cutting depths a_p. Therefore the more intensive cooling of the cutting zone, the less thermal interactions on the on the outline of a workpiece. Modelling of such phenomena has sense only when it is the integrated modelling of thermal interactions of a process, tool and workpiece.

6. CONCLUSION

The problem of mutual thermal interactions in a machine tool, tool, device and cutting process is reduced to the identification of resulting interactions of mentioned components of a technological system on the multi-parameter machine precision of a workpiece. If the machining must be precise, then the workpiece itself must be also taken into consideration in the interaction chain – precisely, its deformations. Above mentioned mutual interactions: environment – machine tool, machine tool – workpiece, process – workpiece, require additional complements and integrations, in order to make it possible to comprise simultaneously all interactions in one integrated model and is still a goal to be realised. On a present stage of research, the identification of thermal interactions in a machine tool on workpiece errors is relatively well mastered, even for very high rotational speeds of a spindle. This can be the basis for the significant compensation of errors of such kind. Relatively little knowledge is available in scope of identifying the influence of the device working in a complex cutting environment.

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