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ADVANCED THERMAL MEASUREMENTS OF MODERN MANUFACTURING SYSTEMS

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Abstract − The paper presents some new measurements and instrumentation paying a special attention to the thermal behaviour of modern manufacturing systems. Acording to a CIRP evaluation, more than 50% of the machining errors, even in the case of modern machine tools, are due to the thermal phenomena. The study of thermal behaviour for machine tools is very important for precision processing, e.g. grinding. The problem is more complicated due to thermal field variations in space and time. The studies and the tests carried out (the thermography used by the author for the first time in Romania) were focused on the optimization of the Romanian grinding machines with the scope to achieve a better quality. The paper presents the author’s results some of them carried out at the Technical University of Cluj-Napoca, Romania, and other at the University of Stuttgart granted from the NATO Science Programme.

Keywords: thermal behaviour, machine tools, Thermography.

1. INTRODUCTION

Actual manufacturing machines must follow a repeatable and accurate behaviour. Unfortunately, thermal deformations up to 150 microns can be found e.g. in milling machines working at medium load. This phenomenon is found also (in other scale but with similar relevance) at the industrial robots, in coordinate measuring machines (CMM’s) or in precision machining equipment. According to a CIRP evaluation, more than 50% of the machining errors even in the case of modern machine-tools are due to the thermal phenomena. In fact the errors having static, dynamic causes or resulting from wear have been in greater proportion already studied and obviated.

The significance and the necessity of the study of the thermal errors is emphasized by the studies of several researches-the majority of them being members of CIRP- and are quoted by Bryan, in the "International Status of Thermal Error Research"[1]: as “ still the largest single source of dimensional errors and apparent non-repeatability of equipment." Others authors carry on [2]: "The economic significance of thermal effects must be relatively high...about 50 to 60% of the errors in precision parts result from thermal errors"; or [3]: "the percentage of error from thermal effects may lie between 40 and 70%".

Thermal stability, as a global concept, is seldom mentioned as a characteristic of machine tools, neither is it checked during acceptance tests.

2. ADVANCED OPTIMISATIONS CONCEPTS APPLIED TO THE THERMAL BEHAVIOUR OF MODERN MANUFACTURING SYSTEMS

A very important aspect is the connection between metrology and the thermal behaviour of machine tools. A condition for the assurance of quality parameters at machine-tools are both its reception and especially its behaviour at different trials.

The reception of machine tools concerns the construction's accuracy, but it is only partial relevant for its accuracy during operation. The final aim is the knowledge and the maintenance of processing accuracy under the influence of all environment conditions and during different mechanical and operating conditions.

In many cases solutions were produced from the work carried out, but they were limited to the specific machine tool, and the basic working conditions were defined exactly. Until now a general and complete (mathematical) description of thermal behaviour of machine tools which is dependent on internal/external heat sources and time , particularly under practical cutting conditions, could not be found.

The research in the thermal deformation field of machine tools has been intensive in the last years. Some authors have dealt with theoretical approaches about the heat transfer in the machine and their relationships with the thermal deformations. Others focused their researches on how to improve the design of the machine to avoid thermal errors. Good machine design can minimize thermal machine deformations, but it is seldom possible to avoid these deformations completely. Other researchers have gone deeper in techniques to compensate the thermal errors using multivariable linear regression techniques, modeling techniques based on neural networks or the Fuzzy-Logic method. Under these circumstances some authors are using the fuzzy-logic method who assigns every object quantitative affiliations to a certain set in the interval [0, 1].

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One of the greatest advantages of this affiliation rule is the ability of fuzzy-logic method to control mathematically, non- or only inadequately ascertainable processes, also.

In the fuzzy-logic applications the input and the output quantities of the fuzzy control unit are often described as fuzzy-sets and characterized through linguistic variables.

Neural Networks are actually one of the preferred methods to tackle the thermal deformations problem in machine tools. The main advantages a neural network provides are:

- this network can learn linear and non-linear models without any extra analysis effort by the operator;
- you don't need to know a previous model which relates temperatures and deformations;
- you can automate most (if not all) the operations.

Anyway, some disadvantages are present, also:

- it is not easy to program a neural network in a very simple PLC;
- you could need an external computer device;
- you must decrease the number of sensors in order to reduce costs and to make the machine more easily maintainable (especially in the industrial applications);
- the automation of the computation techniques in the aim to avoid the presence of experts in the phase of the estimation of the algorithms' parameters;
- the stability of the model along the lifetime of the machine.

The aim is to achieve an integrated determination of the thermal behaviour of machine tool (through precise measurement techniques), to analyze the complete correlation of thermal effects, as well as the existing specific machine conditions and to find the most appropriate measures to keep a high working precision. In this sense, the international standards have advanced continuously. Here we differentiate the strictly necessary measurements from those designated to offer a complete view of all combined influences. After all, this is an economic problem, the costs for evaluation of all influences mentioned above upon machine's behaviour, being considerable. Taking into account the development and the extent of machine tools use, an integrated concept for testing the machine tools in combined stress (static, thermal, dynamic) is very important and of present interest, but relative difficult to realize. On one side, the machine tools producers would like simplified and efficient norms, and on the other side, the beneficiary would like exhaustive norms.

The relationship temperature/displacement (between tool and work piece, composed from 2D or 3D deformations and inclinations of machine tool parts) is in general random and not easily mathematically to describe. The relationship is complicated from the evolution in time of this phenomenon.

A large variety of methods for calibrating and checking machine tools and coordinate measuring machines (CMM) has been applied during the last years. These methods either furnish comprehensive information on the machines' condition, but require much time, effort and expensive equipment, or they are easy to use but give only a general impression of the machine accuracy. The ideal method for reception, acceptance tests and periodic inspections of machine tools or CMM's will have to combine some important properties:

- an accuracy suited for the majority of precise machine tools or CMM's worldwide installed, should be reached;
- the traceability by calibration to national/international standards of length, asks for stable reference, objects or reference measuring instruments which can be calibrated;
- the concept should follow a uniform approach (calibration, acceptance tests and inspections should be possible with the same hard- and software);
- the results of the above mentioned operations should stating the same quality parameters (the user should be able to deduce the uncertainties from these parameters);
- compatibility with existing standards, but the method can not neglect the necessity of development for international standards.

3. APPLICATION AREA AND RESEARCH COURSE

As an important metrology application the author has shown, [4], for the first time in Romania at machine tools, the importance of the thermo graphic method for determining the isothermal field and elaboration of thermal map on grinding machines. More as 100 of thermograph of the Romanian grinding machines were realized and interpreted.

The author started from the fact that, for testing and reception of machine tools, is necessary a fast, precise and efficient identification of the heat sources localized inside the machine body (position and intensity). In this sense, the thermal field determination method, using infrared detectors has provided to be very operative and precise. By its using, the engineers will settle with high precision too, the technological system's zones affected by thermal causes errors. This method is more useful in the case of high precision cutting machine tools, as those of grinding used by the author for his experimental researches. Today, through the low prices of thermo graphic cameras and the appearance of the adequate software for analyzing images and thermal field interpretation, the thermo graphic method becomes an indispensable instrument for analyzing the machine tools behaviour.

The author's studies were carried in two stages: one of them at the Technical University of Cluj-Napoca, Romania in collaboration with a grinding machine factory and the other, with the colleagues of the Institute for Machine Tools, University of Stuttgart-Germany. The studies and the tests carried out in Romania were focused on the optimization of the design and technology of Romanian grinding machines.

The studies of the Romanian grinding machines development were focused, regarding the constructive optimization, upon the basic model of the R.P.O.- R.P.V. family, namely the R.P.O.-200 machine, with adaptation possibilities to others machines.

The constructive alterations aimed the principal sub ensembles identified through researches, to be more affected by thermal stress. The achievement of these constructive improvements concerned a general view of the unit behaviour (or even the whole machine), not only its thermal stability. The author has work out on comparative study about the constructive and kinematics analogy of different grinding machines models in the family R.P.O.- R.P.V., so called "Baukastensystem". Between the calculated (with an analogy coefficient M = 1,6) and the real table's dimensions, starting from the model 125 x 400 up to the model 500 x 4000, are only some little differences in the whole family. The analogy coefficient was calculated based on the increasing of table's dimensions of three models: R.P.O. (R.P.V.) 200 x 630; 320 x 1000 and 500 x 1600. At other grinding machines from abroad, the M coefficient is between 1, 6 and 1, 7, [4]. The same analogy was observed in the other component's construction of R.P.O. - R.P.V. family and also in the distribution of the internal heat sources.

The grinding machine's areas on witch the measurements were made, in the different working days, were marked as follows:

Zone A the machine bed; zone A1 (frontal bed, right down); zone A2 (frontal bed, left down); zone A3 (back bed). Zone C1 (frontal detail with center on the slide the region of the hydraulic block); zone C3 (slide right), zone F (guides right slide), zone G (guide left slide). Zone H (vertical beam), zone H1 (lower vertical beam), zone H2 (lower vertical beam in the area of the grinding head), zone H3 (cover of vertical beam). Zone I (the oil of the tank in the machine bed). Zone K (the hydraulic block). Zone L (the housing of the hydraulic pump).

For the temperature measurement were used thermocouples and thermistors, especially adapted by the author to the different conditions in the grinding process. In this way the author has realized some devices for surface measurement (with magnet), for interior body of some machine parts (with thread and adjustable nut) or for liquids and air. The temperatures determinations have taken into account the influence of the external heat sources, also. Thus in some hot days the temperature of the hydraulic plant have exceeded the value of 60o C (especially the pump and the tank). The fact that in some cases the temperature exceeded 60o C emphasizes the thermal instability of the machine and the opportunity of the optimization solutions. The measured temperature values in the same point, but in several days, were mediated and these values for up to 12 points contributed to the mean value of the measured zone in the machine tool (according to the Romanian standards).

The most important intern heat sources observed at the R.P.O.-200 machine are: the hydraulic plant with the hydraulic pump (max. temperature 58, 5 o C), hydraulic block (max. temperature 50, 2 o C), and hydraulic tank (max. temperature 55,1o C); the electric motors, the gears and guides. The grinding head, due to the bearing solution is in this case, not an important heat source.

The author has calculated also (with a Finite Element Program) the values of temperature in different regions of the machine. As the Figure 1 shows, for the case of hydraulic tank, the difference between the measured and calculated temperature values is minimal.

Table 1: Table 1.The values of experimental temperatures in main areas of the R.P.O. – 200 M machine (°C)

Nr.	Time min.	Zone code											
		A_1	A_2	C_1	C_3	F	G	H_1	H_3	I	K	L	Air
1.	0	19.5	19.3	19.6	19.4	19.1	19.8	22.5	20.0	20.7	19.9	20.6	21
2.	15	20.6	20.3	20.7	20.2	19.8	20.1	23.2	21.2	28.5	25.2	29.2	21.4
3.	30	21.7	21.2	22.4	21.6	20.5	21	24.7	22.5	32.7	28.4	34.0	21.6
4.	45	23.2	22.7	24.5	22.9	21.6	21.9	26.2	24.0	35.6	31.7	36.3	21.5
5.	60	24.6	23.8	26.0	23.8	22.6	22.8	28.1	25.4	36.7	33.1	38.4	21.7
6.	75	26.1	24.8	27.4	24.9	23.8	23.8	29.4	26.5	39.2	34.3	40.5	21.7
7.	90	27.8	25.9	29.1	26.0	24.9	24.9	30.7	27.8	41.2	36.6	42.9	22.3
8.	105	28.6	27.1	30.2	27.1	25.8	25.8	31.9	28.5	43.2	38.2	44.8	22.2
9.	120	30.1	28.4	32.5	28.2	26.8	26.9	32.8	29.5	44.1	39.8	46.0	22.4
10	135	32.4	28.8	33.7	29.6	27.7	27.9	34.2	30.4	45.7	40.6	47.1	22.6
11	150	33.1	29.6	34.8	31.0	28.6	29.0	34.8	31.2	46.2	41.9	48.2	22.7
12	165	33.3	30.4	36.0	32.2	29.3	29.8	35.2	31.3	46.9	43.1	48.9	22.6
13	180	34.8	31.2	37.1	33.1	29.9	30.7	36.0	32.0	47.7	43.9	49.9	22.7
14	195	35.6	31.9	38.0	33.8	30.6	31.4	37.8	32.2	48.2	44.6	51.2	22.8
15	210	36.2	32.5	39.2	34.7	31.3	32.2	39.4	32.4	49.1	45.2	52.4	22.9
16	225	36.9	33.3	40.2	35.6	31.9	32.8	40.9	32.5	49.5	45.8	53.2	23.0
17	240	37.5	34.4	41.0	36.5	32.4	33.3	41.8	32.7	50.2	46.0	54.1	22.9
18	255	38.1	34.6	41.6	36.9	32.8	33.9	42.0	33.0	51.1	46.2	55.2	23.0
19	270	39.2	34.8	42.1	37.4	33.3	34.5	42.4	33.8	51.9	46.8	56.3	23.1
20	285	40.3	35.1	42.7	38.1	33.6	34.8	42.8	34.7	52.6	47.9	56.9	23.2
21	300	40.9	36.9	43.0	38.6	35.0	36.5	43.0	34.7	53.2	49.0	57.6	23.1
22	315	41.5	38.1	43.7	39.3	35.9	37.0	43.1	34.8	53.8	49.7	58.0	23.3
23	330	42.0	38.2	43.8	40.0	36.2	37.2	43.2	34.9	54.2	49.9	58.1	23.2
24	345	42.4	38.4	43.9	40.3	36.3	37.3	43.3	34.9	54.6	50.1	58.3	23.1
25	360	43.1	38.6	44.2	40.7	36.4	37.5	43.3	35.2	55.1	50.2	58.5	23.3
26	375	43.0	38.5	44.2	40.8	36.5	37.4	43.2	35.3	55.0	50.3	58.6	23.2
27	390	43.1	38.6	44.2	44.7	36.4	37.5	43.3	35.2	55.1	50.2	58.5	23.2

As a result appeared that the most important errors due the thermal behaviour are the alteration of the parallelism and rectilinear movements of (or relative to) the principal parts of the machine (table, slide, etc.).

Considering the origin and the disposing of the heat sources, it is necessary to decrease the amount of heat produced inside the machine and those provided from outside and to avoid the temperature differences among different sub ensembles, or even inside the same element.

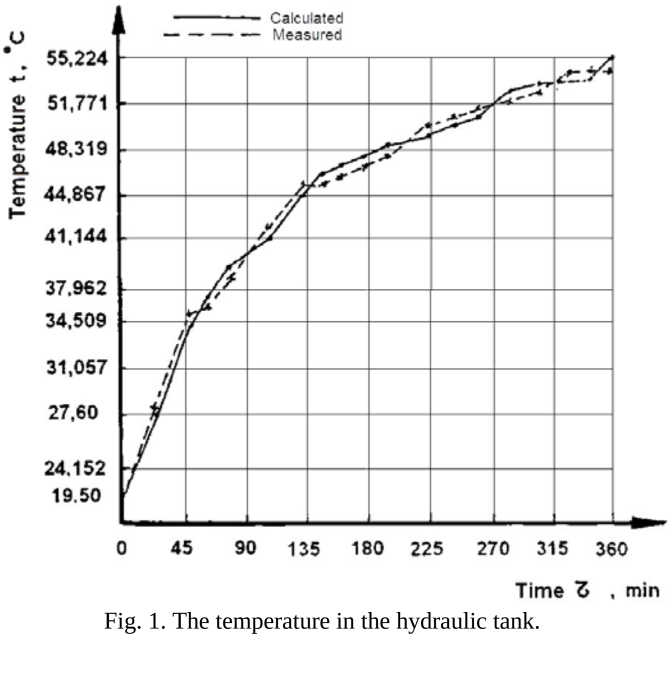

Fig. 1. The temperature in the hydraulic tank.

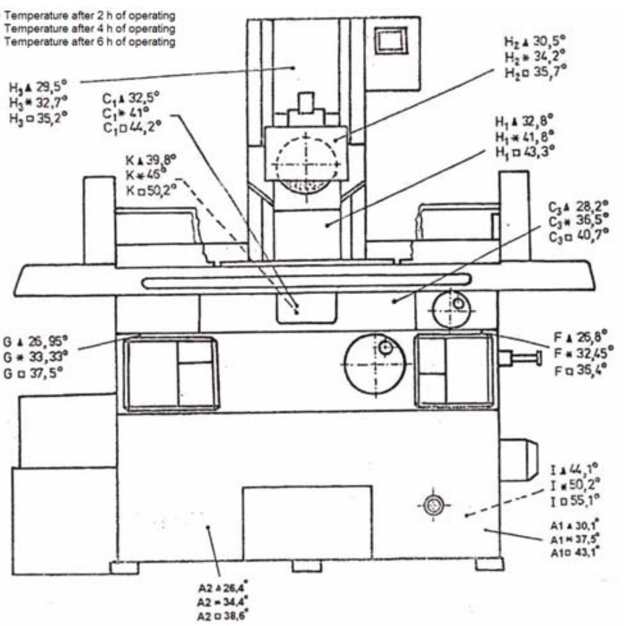

Fig. 2. Thermal map of the grinding machine R.P.O.-200 M.

From the designing stage, the realization of a thermo symmetrical machine contributes to the achievement of a stable thermal behaviour. The thermo symmetry is a balance of geometrical elements loaded as much as possible with a uniform temperature distribution. Many grinding machines factories allow a great importance to this concept, which is linked with the notion of thermal stability of the machine tools, the working accuracy being acquired and maintained during the whole working day. These options depend to a great extent of the system structure concept and the position of the hydraulic group.

A thermal behaviour representation in time, until stabilization - Fig. 2- of the most important machine zones, was elaborated from the author as a "thermal map" [3].

An other research project, carried out at the Machine Tool Institute of Stuttgart University where the author was integrated for a period ("Analysis of thermal behaviour of new types of machine tools") was based on the HEXACT machine type (Parallel Kinematics developed from IFW-University of Stuttgart) /8/, Figure 3

The importance of the heat sources inside the HEXACT machine is represented in Figure 4, as one of the author thermographs.

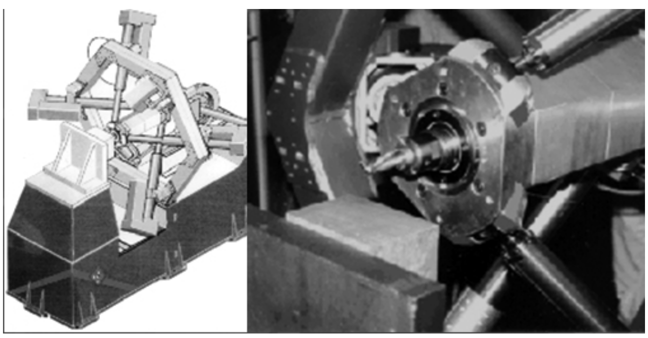

Fig. 3. The HEXACT machine developed at IFW-University of Stuttgart

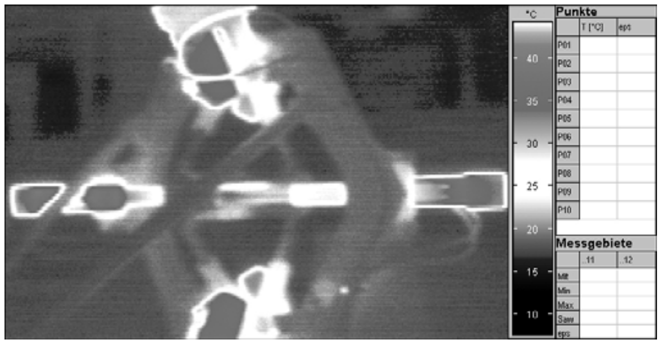

Fig. 4. Thermographs of the HEXACT Frame

One of the most important conclusions of this research work, where some thermal optimization solutions for the Romanian machine tools, with the aim of machining precision improvement.

4. CONCLUSIONS

The author has carried out for the first time in Romania, the thermo graphical study of machine tools. The experimental results, problems identification, methodology, results processing, conclusions and author's practical solutions for a better quality precision and testing of Romanian machine tools, are presented in /4/, /5/, /6/, /7/.

Thermal errors appear in generally as the alteration of slide's and table's smoothness, respective as the disorder of parallelism between the grinding head and the table. Executing the measurement of the straight-line on the surface of the table, in longitudinal, transversal and diagonal direction at the machine RPO – 200 M the registered deviation, from the admissible value of 0,010 / 1000 mm length is 0.002 mm -0,010 mm (convex) in compared with. After 4 hours of functioning the measurements were remade with the result of 0,010 mm (concave) deviation. The curvature of the table has changed his sense, this shows reported to the initial value a doubled error. Beside the changes of the absolute value, the changing of the curvature has negative effects on the processing of the piece. The smoothness of the piece was measured in parallel with the temperature measurements each 15 minutes. The errors of the piece along 345 minutes of measurements are between +0,028 mm and -0,022 mm, compared to the admissible 0,005/300 m. After 240 the errors in the 5 measured points of the piece became positive and started to group.

This shows the strong influence of the slide's (hydraulic block placed inside) thermal instability regarding the table and the processing precision. The internal thermal influence of the table (hydraulic cylinder) is smaller than the influence of the slide on the table. The solution was getting out the hydraulic block from the slide and to put it in the cradle. With the necessary modification to the hydraulic installation, the block became fix not mobile with the slide.As conclusions and recommendations in our research project with the company was considered opportune (in the free space from the hydraulic block) to raise the rigidity of the slide through ribs.

An optimization of the hydraulically bloc under thermal aspect (especially those with high powers) is removing the raising of temperature by using a pump with variable flow (instead with constant flow). This solutions which is justified for the high precision grinding machines will be mounted on the new type of RPO (RPO 500X) as on other practical improvement of our researches in the factory .

The problem on raising the hydraulic tank so that a bigger quantity of oil leads to a slower recirculation and to a more efficient cooling of the installation can be solved with a mixed tank interior – exterior simply by adding a tank. The circulation of oil between these tanks would lead to a more efficient cooling. Placing the tank inside or outside must be considered economically, the solution with the tank outside the machine would be thermal better but more expensive.

More RPO 200 M to be more thermal stabile, was modified with exterior hydraulic tanks, like formulate in our research project with the company. It is preferred the solution with separate hydraulic tank for the high precision machines (RPO -200 S-A), designate to the automotive industry.

Parallel to perfecting the hydraulic system the S.A. machine has a vertical and transversal feed precision of 0,0005mm and is equipped with a step by step motor and screw with balls (forward feed) numerical display, automatic correction compensation of the used disc, variable speed of the main shaft.

Due to the constructive, geometric, and functional analogies and the modular development of plan grinding machines RPO-RPV from the base module RPO 200 M, the constructive changes do not regard a singular case, but cause the whole series RPO-RPV. For the models RPO-RPV -320 and RPO-RPV -500 by raising the power, the optimization of the thermal behavior is more necessary as for the base components of the RPO -200.

Another major conclusion of the authors' researches is a classification of the thermal behaviour optimization measures for machine-tools testing:

- the uniform distribution (equalization) in the whole machine tool of the inevitable temperature increases, through a adequate distribution of the thermal sources in sub ensembles;
- the decrease of the energy amount converted in heat, namely the intensity of thermal sources;
- the ensuring of heat transfer, the intensification of heat exchange with the outside, through the extending of the exchange surfaces and the increasing of the thermal convective coefficient;
- the cooling of the machine surfaces and the use of oil thermostatic control;
- the ensuring of climatization conditions in hall;
- the diminution of errors through compensatory systems.

As soon as these steps will be assured from the beginning of the designing - achievement cycle, both for the prototype and the serial production, it will be augmented a greater efficiency and a better quality management.

In conclusion, for an optimize thermal behaviour of machine-tools and robots it is necessary in the first time, to decrease the inside heating and to reach in short time, stationary thermal working conditions, simultaneous with a how much uniform distribution of the temperature field in the whole technological system.

Together with the team of the Stuttgart University were identified some new useful concepts for the Romanian machine tools industry, also:

- the new structure concept of HEXACT studied by the author, in parallel with an other machine types developed in Stuttgart, may have good prospects for the Romanian machine tools components also;

- modular and reconfigurable machine tools and Reconfigurable Manufacturing Systems (RMS) can play an important role for the existing Romanian machine tools;

- the correlation among vibrations, temperature distribution and the noise of mechanical system can improve the existing constructive projects of Romanian machine tools;

- identification of the machine complex signature in order to diagnose the state of the machine and to perform a preventive maintenance.

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