

# QUALITY MANAGEMENT AND TEMPERATURE MEASUREMENT IN MACHINE TOOLS AND ROBOTS

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*Abstract: Thermal effects are still the largest single source of dimensional errors and apparent non-repeatability of technological equipment. The thermal stability of robots and machine tools, both in the phase of machining as in that of testing and reception, must also be connected with quality assurance and quality management.*

*The author has studied more than 20 years the optimisation of thermal behaviour of machine tools and he had his doctorate in this field. Also, the author has used, for the first time in Romania, the thermographical study at the machine tools, and has determined on this way the isothermal field and the thermal map for machine tools. The paper presents some results of the author's research at the Technical University of Cluj-Napoca and others together with the colleagues from the Vienna University of Technology or the University of Stuttgart.*

*Keywords: temperature measurement; quality management; thermal behaviour*

## 1 INTRODUCTION

Apart from static and dynamic stresses, the behaviour of machine tools and robots is affected by internal and external sources of heat. The thermal errors, in case of machining, can be as great as the total nominal tolerance itself, while the errors having static, dynamic causes or resulting from wear, have been in greater proportion already obviated. Therefore today is very important and very actual to continue the optimisation study of the thermal behaviour of machine tools, industrial robots and coordinate measuring machines.

The author has studied the thermal field and thermal errors of machine tools more than 20 years, and he had his doctorate in this domain. The three-dimensional isothermal field of a machine tool can be changed due to thermal disturbances. The thermal field depend on machine part geometry, on thermal properties of machine materials and on the mechanics of heat transfer between machine parts and the environment. The paper presents some results of the author's research at the Technical University of Cluj-Napoca and others together with the colleagues from the Vienna University of Technology or the University of Stuttgart, making also use of a thermostatic large-sized cabin, a laser interferometer system for the measurement of geometric parameters with automatically programming and interpretation of the measurements.

According to a CIRP evaluation "International Status of Thermal Error Research" (1) the "thermal effects are still the largest single source of dimensional errors and apparent non-repeatability of equipment" and more than 50% of the machining or measuring errors, are due to the thermal phenomena. McKeown, Weck and Bonse (2) give in 1995 an comprehensive study about the thermal errors of machine tools, also in Annals of the CIRP.

The thermal stability of machine tools and industrial robots, both in the phase of machining as in that of components testing and reception, must also be connected with quality management, quality assurance and a correct concept of CAQ ( Computer Aided Quality). The importance of this problem was already emphasized by a series of standards issued worldwide, as ISO 230, ISO 1701, DIN 8601, DIN V 8602, DIN 8605, VDI/DGQ 3441 or ÖNORM M 9115. Finally the tests are designed to establish the relative displacements between the tool and the workpiece, as a result of thermal errors of robot or machine tool. Some german authors defined the "thermic chain", from the input of energy in the machine tool, until the workpiece, Fischer ( 3).

A new trend is represented by a new, unitary concept for the reception and machine-tools testing, as DIN V 8602, which integrates the thermal behaviour into a global concept taking into account the simultaneous solicitation of machine-tool (static and thermic factors). A condition for the precision assurance of machine-tools and robots is both the reception and the verification of the technological equipment behaviour at different trials ( e.g. thermic and static stress). The final aim is the knowledge

and the maintainance of processing accuracy under the influence of all environment conditions and during different operating conditions.

In order to maintain tolerances during manufacturing, assembling or measuring processes, machine tools, industrial robots and measuring machines are required to perform within high accuracy. In 1973, the accuracy of 60% the european industrial robots were within the limits of  $\pm 1$  mm. After twenty years approximately 40% of robots performed within repeating accuracy of 0,01 to 0,05 mm (1).

The same importance of the thermal behaviour is relevant for handling, assembling or measuring precision, in case of robots or coordinate measuring machines.

## 2 TEMPERATURE MEASUREMENT AND THERMAL BEHAVIOUR OF MACHINE TOOLS

The thermal behaviour of machine tools was earlier studied as that of robots.

Starting from the '50-th years many authors studied the thermal deformation and the thermal errors of machine tools (turning, milling), (10), (11). In the '60-th years appeared some researches about grinding machines (12), and also for other machine tools (13), (14), (15), (16). Due to the complicate concatenation causes-effects (heat sources- errors) both variable in space and time, to inadequate mathematical methods and to insufficient memory of computers the solutions have had only a limited target or result. Only with advanced mathematical methods (e.g. the Finite Element Method) and with performant computers was later possible to achieve more extended solutions to determinate the thermal and the deformation field, and also to minimize the errors.

The author work out a comparative study of the design, construction, structure and thermal behaviour of the most important grinding machines (Blohm, Elb, Tos, Voumard, Danobat, Studer, Toyoda, Jones-Shipman, Schaudt, etc.).

The development study of the romanian grinding machines was focused, regarding the constructive optimization, upon the basic model of the R.P.O.- R.P.V. family, namely the R.P.O.-200 M machine, serial no. 5480, with adaptation possibilities to others machines.

The author's constructive alterations aimed the principal units 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.

A representation of thermal behaviour of the machine, in time, until stabilization, regarding the most important zones, was elaborated from the author as a "thermal map".

Because of constructive, geometric and functional analogies, as well as modular development of the grinding machines family R.P.O.- R.P.V., the constructive optimizations of the model 200 M, doesn't aim only a singular case, but also the whole grinding machines family R.P.O.- R.P.V. By increasing the installed load and the motor speed at the machines type R.P.O.- R.P.V.-320 (e.g. 5,5/ 6,5 kW and 1500/ 3000 rot/min) or R.P.O.- R.P.V.-500, the optimization measures of thermal behaviour are more necessary, but the development of greater entities preserves the solutions and the optimizations of the basic family model R.P.O. 200.

Very interesting is the author's 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 125x400 up to the model 500x4000, 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.) 200x630; 320x1000 and 500x1600. 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 most important intern heat sources observed at the R.P.O.-200 machine are: the hydraulic plant with the hydraulic pump (max. temperature  $58,5^{\circ}\text{C}$ ), hydraulic block (max. temperature  $50,2^{\circ}\text{C}$ ), and hydraulic tank (max. temperature  $55,1^{\circ}\text{C}$ ); the electric motors, the gears and guides. The grinding head, due to the bearing solution is not an important heat source.

For the temperature measurement were used thermocouples and thermistors, specially adapted from the author, to the different conditions in the grinding process. So the author has realised 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 temperature determinations have take into account also, the influence of the external heat sources. Thus in some hot days the temperature of the hydraulic plant have exceeded the value of  $60^{\circ}\text{C}$  (especially the pump and the tank).

The fact that in some cases the temperature exceeded  $60^{\circ}\text{C}$  emphasize the thermal instability of the machine and the oportunity of the optimisation 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 e.g. STAS 6679).

The most important machine parts affected from the internal heat sources are: the slide, the frame (with the hydraulic plant inside), the table and the vertical beam (with an electric motor inside and with an insufficient ventilation due to the electric plant disposed on the beam's back).

At the frame was observed also a strong temperature variation not only in the length, but also on the high (up to 10° C), due to the hydraulic tank based inside.

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

The author has shown, for the first time in Romania, the importance of the thermographic method for determining the isothermal field and the thermal map for machine-tools (4). The thermographic method was extended today to the determination of the thermo-elastic deformation.

The author started from the fact that for industrial testing and reception of machine-tools is necessary a fast, precise and efficient identification method concerning heat sources localized inside the machine body (position and intensity). In this sense, the isothermal field determination, using infrared detectors has proved to be very operative and precise. By its using, the engineers will settle with high precision the zones of technological system, affected by thermal 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 thermographic cameras and the appearance of the adequate software for images analyzing and thermal field interpretation, the thermographic method becomes an indispensable instrument for behaviour analyzing of machine tools and robots.

After the fast identification of the principal heat sources with the thermographical method, the measurements can be concentrated on different zones of the machine tool using a big number of thermocouples and thermistors connected final to the computer.

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 units, or even inside the same element.

From the designing stage, the realization of a thermosymmetrical machine contributes to the achievement of a stable thermal behaviour. The thermosymmetry is a balance of geometrical elements loaded as much as possible with a uniform temperature distribution. Many grinding machine 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. Concerning the construction of precise and high precision machines, the solution with separate hydraulic tank, is preferred.

The author worked out also a mathematical model, using the Finite Element Method, for the rapid determination of the thermal field of various machine tool components. The program can be used for different components of machine tools or robots and has the advantage that can quickly analyse different arrangements of heat sources inside the machine tool, choosing the best constructive solution.

The studies and the tests carried out in Romania, at the Technical University of Cluj-Napoca, in collaboration with a grinding machine factory, were focussed on the optimisation of construction, design and technology of Romanian grinding machines with the scope to achieve a better quality management in the Romanian machine tools factories. The improvements carried out from the author contributed to a better quality and precision of Romanian machine tools and also to a better technological organisation inside the factory where the author was working for more than 5 years (4). There was a first step (in the years '70-'80) of the quality management in Romania, according to the international standards, and for the improvement of national standards.

Latter the studies were continued with more sophisticated instruments and tests at the University of Stuttgart, making also use of a huge thermostatical cabin. Other studies were carried out with the colleagues from Vienna University of Technology, developing at a higher level the links between industrial metrology, reception of machine tools, quality management and international standards on the one side and thermal behaviour and thermal stability of machine tools and industrial robots, on the other one.

In conclusion, according to the author's researches, for an optimum thermal behaviour of machine-tools, is necessary in the first time, to decrease the inside heating and, to reach in short time, as uniform as possible temperature distribution, in the whole technological system (stationary thermal working conditions).

A short classification of the thermal behaviour optimization measures of machine-tools can comprehend the following aspects:

- a) the decrease of the energy amount converted in heat, namely the intensity of thermal sources;
- b) the uniform distribution (equalization) in the whole machine-tool of the inevitable temperature increases, through a adequate distribution of the thermal sources in subensembles;
- c) 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;
- d) the cooling of the machine surfaces and the use of oil thermostatic control;
- e) the ensuring of climatization conditions in hall;
- f) the diminution of errors through compensatory systems;
- g) the correction of thermal errors through NC-systems;
- h) the thermal deformation compensation using modern mathematical methods (e.g. Neural Network, Fuzzy-Logic).

### 3 THERMAL BEHAVIOUR OF ROBOTS AND COORDINATE MEASURING MACHINES. NEW TRENDS IN MANUFACTURING SYSTEMS

The precision of manufacturing, handling, assembling or measuring and the flexibility concept have become an important requirement at all levels of manufacturing industry.

The thermal behaviour of robots was later explored als the thermal behaviour of machine tools. Only in the '70-th years were published studies about the behaviour of robots with electric and hydraulic drive. Especially the robots with hydraulic drive have thermal problems. At the robots with electric drive are not serious problems with the TCP (tool center position). Otherwise in a period of 20 years (1973-1992) the robots precision increase between 70% and 100%, till 0,01-0,05 mm, in the year of 1992 ( 6).

In case of robots the thermal behaviour of different separate components is very importante and with a great influence on the Pose of TCP ( Pose = position and orientation of the robot's TCP; EN 29283). It is also necessary to develop special measure models to determinate the thermal displacements of the different components.

Most Departments of Stuttgart University work out a lot of researches in the domain of thermal behaviour and the improvement of robots precision (7), (8), (9).

Although DIN V 8602 refers to machine-tools, its problems are reflected upon measuring and control equipments, too. Thus, the assurance of thermal stability is acutely raised for the producers of measuring equipment and instruments, some of these being veritable measure and control centres.

The complex measures start from the using of some special materials as ZERODUR (with a very small coefficient of thermic dilatation:  $0 + 0,05 \cdot 10^{-6} \text{ 1/K}$ ) till technological measures (CARAT plated slides) and exploitation measures ( thermostatic cabins or precints, very strict controlled).

The Cartesian Measuring Machines, i.e. CMMs, have a very simple kinematic configuration, the high accuracy can be achieved with pretentious designing steps, with the highest manufacturing precision of the key components, with a rigid construction of components ( i.e. granit table) and of linear axis and final with linear measuring systems of highest accuracy.

To make the CMMs more convenient for workshops, a combination between robots and CMMs, the so called "measuring robots" were developed. However the CMMs have some important inconvenients: can not be easily transported from one place to another, or can not be easily integrated directly into the manufacturing process (17).

A completely new dimension in the measuring techniques are the portable coordinate measuring arms with rotational axes, i.e. the MOLLI ( Mobile Linear Longitudinal Instrument) system, loaded with the antthropoidic measuring device AMG-1. Measuring devices with rotational axes can achieve an error limit from 0,005 mm, i.e. the Zeiss Scan-Max, Scara type (17).

In the last time, the researchers have developed worldwide, some new concepts of machine tools and robots. An example is the HEXACT (machine with parallel kinematics) developed at the Stuttgart University. At those machines the thermal behaviour is a very important factor for the final machining precision. All rods of this machine tool, designed in the Hexapod style, are always under tensile loading due to the arrangement of main drives and thermal deformations occur, due to large linear expansions of the arms (7).

In the field of machine tool design occur today different new trends. The High-Speed-Technology (HST) and the highly dynamic machines generate new requirements for the machine design (light weight, linear direct drives, new kinematics, open control system).

Terms such as Agile Systems to the High Production Machining (HPM), Reconfigurable Machining Systems (RMS), Holonic Manufacturing Systems (HMS), Bionic Manufacturing Systems (BMS), or Transformation Capable target variable machining systems are presently the object of research in industrialized countrys as Germany, USA, or Japan. The strategic meaning of this new concepts can

be illustrated with one example: the development center for Reconfigurable machining systems at the University of Michigan- USA has a yearly budget of 6 million USD and it is sponsored by over 30 industrial companies. In Germany the SFB Sonder Forschung Bereich 467 "Reconfigurable business structures for the big variety serial production" will run for nine years at the University of Stuttgart.

In all of this new trends the thermal behaviour and the thermal stability will play a very important role.

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