ABSTRACT
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. According to a CIRP evaluation, more than 50% of the machining errors of modern machine tools are due to the thermal phenomena. 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 author explores the problem of thermal behaviour for more than 25 years; the paper presents some tests carried out at the University of Stuttgart, also.

KEYWORDS: Thermal behaviour, Machine tools, Thermography

1. INTRODUCTION
Some authors /1/ consider the variations of temperature as the most important factor among all the influences of medium upon the precision of machining and measuring.

In fact the errors with static, dynamic or wear, causes, have been in greater proportion obviated. Professor Bryan /1/ in his Keynote Paper “International Status of Thermal Error Research” says:

"Thermal effects are still the largest single source of dimensional errors and apparent non-repeatability of equipment". Today is very important also, to connect the optimization of the thermal behaviour with modern metrology concepts and with quality management. The thermal stability of machine tools and robots both in the phase of machining as in that of reception, most be connected with modern quality assurance concepts, also.

Others authors carry on: A. Mottu, /3/ "The economic significance of thermal effects must be relatively high...about 50 to 60% of the errors in precision parts result from thermal errors"; J. Peklenik, /4/ "The percentage of error from thermal effects may lies between 40 and 70%".

Particularly in Europe, little attention has been paid on the thermal stability of machine tools, related standards being still scarce. Thermal stability, as a global concept, is seldom mentioned as a characteristic of machine tools, neither is it checked during acceptance tests. A new trend is represented by a new, unitary concept for the reception and machine tools testing, which integrates the thermal behaviour into a global concept taking into account the simultaneous solicitation of machine tool (static and thermal factors). The latest researches of the author: "Analysis of thermal behaviour of new types of machine tools" were carried out at the University of Stuttgart granted from the NATO Science Programme, with host institute project director: Prof. Dr.-Ing. Dr. h.c. mult. Uwe Heisel, Director of Institute for Machine Tools, University of Stuttgart, Germany.
2. ADVANCED OPTIMISATIONS CONCEPTS APPLIED TO THE THERMAL BEHAVIOUR OF GRINDING AND OTHER TYPES OF MODERN MANUFACTURING SYSTEMS

The research in the thermal deformation field of machine tools and robots has been intensive in the last years. Some authors have dealt with theoretical approaches about the heat transfer in the machine or robot and their relationships with the thermal deformations. Others focused their researches on how to improve the design of the machine and robot to avoid thermal errors. Good design can minimize thermal 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.

The reception process concerns the construction's accuracy, but it is only partial relevant for the 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 or robot, and the basic working conditions were defined exactly. The aim is to achieve an integrated determination of the thermal behaviour (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.

Here we differentiate the strictly necessary measurements from those designated to offer a complete view for the influence of the thermal stress. 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 and robots use, an integrated concept for testing in combined stress (static, thermal, dynamic) is very important and of present interest, but relative difficult to realize. On one side, the machine tools and robots producers would like simplified and efficient norms, and on the other side, the beneficiary would like exhaustive norms.

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 also present:

- 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.

After a long experience of researches in this field, the author established that the optimization of the thermal behaviour of machine tools, robots or coordinate measuring machines is determined by a great number of interconnected influencing factors and the recording of the influence of these factors regarding possible compensating methods is very difficult and uses complicated technologies.

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.
Under these circumstances some authors are using the fuzzy-logic method who assigns every object quantitative affiliations to a certain set in the interval \([0, 1]\). One of the greatest advantages of this affiliation rule is the ability of fuzzy-logic method to control mathematically also, non- or only inadequately ascertainable processes.

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.

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 development of international standards.

3. APPLICATION AREA AND RESEARCH COURSE

The author’s researches started from problems identification of the thermal behaviour and testing of Romanian grinding machines during his five years experience in a Romanian grinding machines factory from the whole concatenation of causes (size, number, extend and position of the thermal sources) up to the final effects and the machining errors.

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The author’s studies of the Romanian grinding machines were focused upon the basic model of the R.P.O. /R.P.V. family, namely the R.P.O.-200 machine, serial no. 5480, with adaptation possibilities to others machines.
The author started from the fact that for machine-tools industrial testing and reception is necessary a fast, precise and efficient identification method concerning heat sources localized inside the machine body (position and intensity). In this sense, the thermal field determination method using infrared detectors was proved 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.

A representation of thermal behaviour of the most important zones of this machine until stabilization was elaborated as a “thermal map” using thermography, as an image processing method. After the fast identification of the principal’s heat sources with the thermo graphical method, the author’s measurements were focused on different zones of the RPO-200 machine, using a lot of thermocouples/ thermistors connected final to the computer.

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, Figure 1.

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. Figure 2 shows one of the authors’ thermographies of a Romanian grinding machine with an internal hydraulic group, as a major thermal source. As conclusion and as one of the real research relevant is the solution with separate hydraulic tank, adopted at the RPO-200 machine, also. The improvements carried out from the author contributed to a better technological organization inside his factory, also.

All the experimental results, from the problems identification to the results processing and conclusions, together with the first author main contribution- a better quality and precision of Romanian machine tools- are presented in his PhD Thesis [2].

Figure 2: Thermography of a Romanian grinding machine.

There was some first steps (in the years ’70 -’80) of the quality management in Romania, according to the national and international standards. These kinds of studies are more necessary in Romania because of the standards lacking and the need of joining to the European norms. The later approach of the thermal behaviour, as compared to the static behaviour, is resulted
from the complex, interdisciplinary character of the problem, leaving from the temporal and spatial existence of a variable thermal field and from a difficult elaboration of a mathematical model harmonious with the real physical model. The mathematical model needs considerable calculation capacities for a wide covering (using for example, the method of finite element) of the whole machine tool structure and an accuracy introduction of boundary conditions.

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. It is very interesting 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 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. 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 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 not an important heat source.

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 also, the influence of the external heat sources. 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 parts of the machine 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 10o C), due to the hydraulic tank based inside.

As a result appeared the most important errors due the thermal behaviour: 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.

One of the latest research projects of the author ("Analysis of thermal behaviour of new types of machine tools") based on the new type of machine HEXACT /8/, was granted from NATO and carried out at the University of Stuttgart, Germany, Figure 3. After identification of the testing problems at this new type of machine the author’s research course has had four steps:

- The study of the new structure of Parallel Cinematic Machine, with the main components: main spindle unit (E. Fisher AG.), control and drive system (Siemens AG.), servo struts and joints (INA), welded body and hexagonal frame;
- The identification of the most important thermal sources in the machine structure (with influence on the machining precision) emphasizing some new aspects in the relation machine construction-thermal behaviour;
Based on the former experience of the author: measurements with the thermo graphical camera INFRATEC, JENAOPTIK and the images saving and analysis (software IRBIS V 1.0 and COREL DRAW 7.0);

**Figure 3:** The HEXACT machine developed at IFW-University of Stuttgart.

**Figure 4:** Thermographs of the HEXACT Frame.

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  The importance of the heat sources inside the HEXACT machine (and their influence on machine deformations) is represented in Figure 4, as one of the author thermographs. The researches emphasize that at the end of the six arms of HEXACT are situated some important heat sources. These sources contribute to some thermal deformation of the thin structure of the arms. Finally, due the sum of these thermal deformations of the hexagonal frame, the manufacturing precision will be affected. Now are running some researches in the aim to optimize the thermal behavior of the HEXACT. It must be emphasized that it is a team work together with the Machine Tool Institute of Stuttgart University conducted by Prof Heisel /8/ and the author was integrated for a period in this team.

6. **CONCLUSIONS**

The author has carried out for the first time in Romania, the thermographical study of machine tools, and he has determined on this way the isothermal field and the thermal map for grinding machine tools /7/. About 100 of thermographies of the Romanian grinding machines were realized and interpreted. All 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 /2/, /5/, /6/, /7/.

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 type PARALIX, 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.

7. REFERENCES
