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INTERNATIONAL STATUS OF THERMAL ERROR RESEARCH

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PREFACE

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INTERNATIONAL STATUS OF THERMAL ERROR RESEARCH

ABSTRACT

This paper is a cooperative effort of the new CIRP Subgroup formed to deal with the overall problem of thermal effects errors in machine tools and metrology. The thermal effects problem is summarized by a diagram which is intended to show all possible forms of thermal error. Existing research literature and the need for new work is reviewed in terms of this diagram.

RESUMÉ

Ce rapport est le résultat d'éffort crée par le nouveau groupe auxiliaire du CIRP, qui a été formé pour opérer dans une fac, on générale, avec le probleme d'erreurs d'effet thermique, produites dans les machines-outils et aussi en metrologie.

Le probleme des effets thermiques est réduit a un diagramme qui présentera toutes les formes d'erreurs possible.

Le diagramme expose l'éxistance actuelles de revue scientifiques et la nécéssité de nouveaux travaux sera nécéssaire.

ZUSAMMENFASSUNG

Dieser Bericht ist ein gemeinsamer Beitrag der neuen CIRP-Gruppe. Letztere wurde gegruendet um sich mit dem Gesamtproblem der Waermeeinfluesse auf die Fehler in Maschinenwerkzeugen und Maschinenmesskunde zu befassen. Das Problem ist durch ein Diagramm illustriert, in dem die moeglichen Arten der Waermefehler dargestellt sind. Eine Uebersicht der existierenden Literatur und der Bedarf neuer Untersuchungen ist mit Hilfe des Diagrammes erleutert.

INTRODUCTION

At the 1966 meeting of the International Institution for Production Engineering Research (CIRP), the significance of thermal effects errors was formally recognized. A special subgroup made up of interested members of the machine tool group and metrology group was formed to deal with the problem. This action was taken partly as a result of the paper submitted by E. R. McClure, "The Significance of Thermal Effects in Manufacturing and Metrology."

The first activity of the new subgroup has been the preparation of this report on the international status of the problem, and what needs to be done about it. The report deals with answers to the following questions:

1. What evidence is available to show that a significant problem does exist, and why has this problem not been recognized earlier?
2. How can the various elements of the problem be classified?
3. What research has been done and what solutions are presently available and what kind of action and research needs to be undertaken in the future?

In the following sections, these questions will be discussed individually.

EVIDENCE OF THE PROBLEM

The fact that a thermal problem does exist is based on the following evidence: (1) the opinion of qualified experts in both machine tool and metrology; (2) the size of recent investments in plant temperature control by machine tool builders and users; and (3) the force of logic of representative case studies that are described in the growing body of research papers.

Some possible reasons for greater recognition of the problem at this time are: (1) the trend toward closer tolerances; (2) the trend toward numerical control with the subsequent elimination of the skilled, self-adaptive man; and (3) the results of continuing research in manufacturing and metrology which has resulted in better instrumentation and methods for breaking down the overall error package into such individual components as tool wear, static and dynamic deflection, kinematic accuracy, and thermal effects.

The possibilities stated above will be discussed individually in the following sections.

Expert Opinion

Some samples of expert opinion follow.

E. Englehard, PTB Braunsweig: "Temperature problems at the present time are the limiting factor in the ultimate determination of length."

H. Opitz, Aachen: "In many cases the errors caused by thermal deformations have the same or higher order of magnitude as those errors due to the kinematic accuracy and the static and dynamic compliance."

E. Merchant, Cincinnati: "The near future will see a concentration of effort to control room temperature. This will be paralled by efforts to isolate or eliminate heat sources in existing equipment. Better thermal design of new equipment will follow."

A. Mottu, Geneva: "I think that the economic significance of thermal effects must be relatively high. From my own experience, about 50 to 60% of the errors in precision parts result from thermal error."

J. Peklenik, Birmingham: "Thermal errors affect the accuracy of machine tools considerably. The increasingly more general application of automatic manufacturing systems may require a wider investigation into the solution of this kind of problem. My own experience indicates that the percentage of error from thermal effects may lie between 40 and 70%."

J. Schunck, Aachen: "In many cases the working accuracy of machine tools is decisively affected by thermally induced changes in shape."

C. Gladman, Sydney: "I consider that the percentage of overall error taken by thermal effects must increase as the demand for precision grows."

B. Breev, USSR: "Errors in machine tools caused by thermal influences are often many times more significant than from various other sources."

Moore and Victory, Bridgeport: "In the use of precision locating equipment, thermal expansion is capable of causing troublesome dimensional changes in both workpiece and machine. This potential reduction in accuracy is neither insignificant nor inevitable."

Size of Investments

The size of recent investments in temperature control is a measure of the collective thinking of some very practical-minded people. McClure's survey of American industry[53] revealed that major machine tool builders and users are investing as much as one million dollars per installation. General manufacturing areas as well as precision assembly and inspection areas are being controlled. This trend is not confined to the U. S. A major machine builder in Switzerland recently announced an investment of $500,000.

Case Studies

The case studies described in the literature offer convincing evidence of the seriousness of the thermal problem. An example, contributed by J. Tlusty of Prague, is as follows:

> "A hole of 210 mm diam was ground on a series of 15 workpieces, using an automatic internal grinding machine with 630-mm swing. The hole diameter on each workpiece was measured; in Fig. 1 the errors with respect to the first workpiece are marked by full line. Measurements of the temperature of the coolant have shown that the diameters ground varied in an analogous way as the variation of temperature. The errors in a diameter are mostly caused by the fact that the coolant which is warmed up by the heat produced in the grinding process falls on the body of the wheel slide and warms it up. The direct heating of the wheel slide body was prevented by means of a sheet metal guard. The effect of this guard is indicated in the diagram by the dashed line which shows the variation of errors in diameter while grinding by using the guard. The scatter of the errors in the comparable cases was reduced from approx. 0.030 mm to approx. 0.006 mm."

CLASSIFICATION OF THERMAL PROBLEMS

Figure 2 diagrams a useful way of visualizing the thermal error system. This diagram provides a convenient means of organizing the subject, and illustrates the fact that a complex system does exist. The diagram reflects two of the concepts proposed in earlier papers by Bryan and McClure[42,51,56]. First, it is helpful to divide the overall thermal problem into the following categories: (1) the effects of uniform temperatures other than 68°F (20°C); and (2) the effects of non-uniform temperatures. The second concept is that every measuring and machining operation unavoidably consists of a three-element system made up of the part, the master, and the machine frame.

The diagram will be used as a basis for discussion of the thermal effects problem in industry today, results of past research work, and the need for new work.

Six sources of thermal influence are shown in Fig. 2: (1) heat generated from the cutting process, (2) heat generated by the machine, (3) heating or cooling influence provided by the various cooling systems, (4) heating or cooling influence provided by the room environment, (5) the effect of people, and (6) thermal memory from any previous environment. Room environment and coolant systems are the only influences

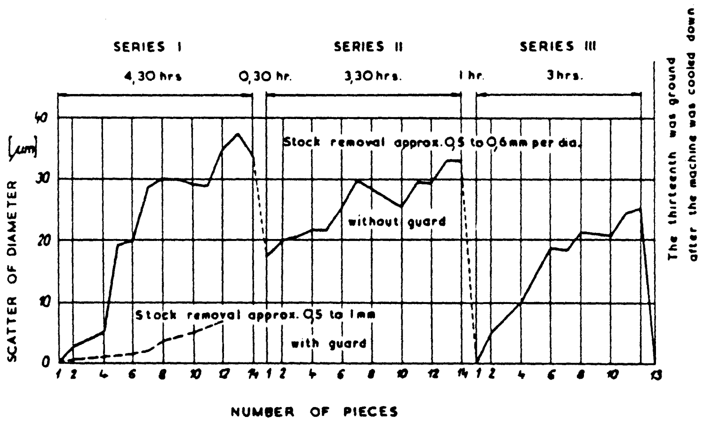

Figure 1

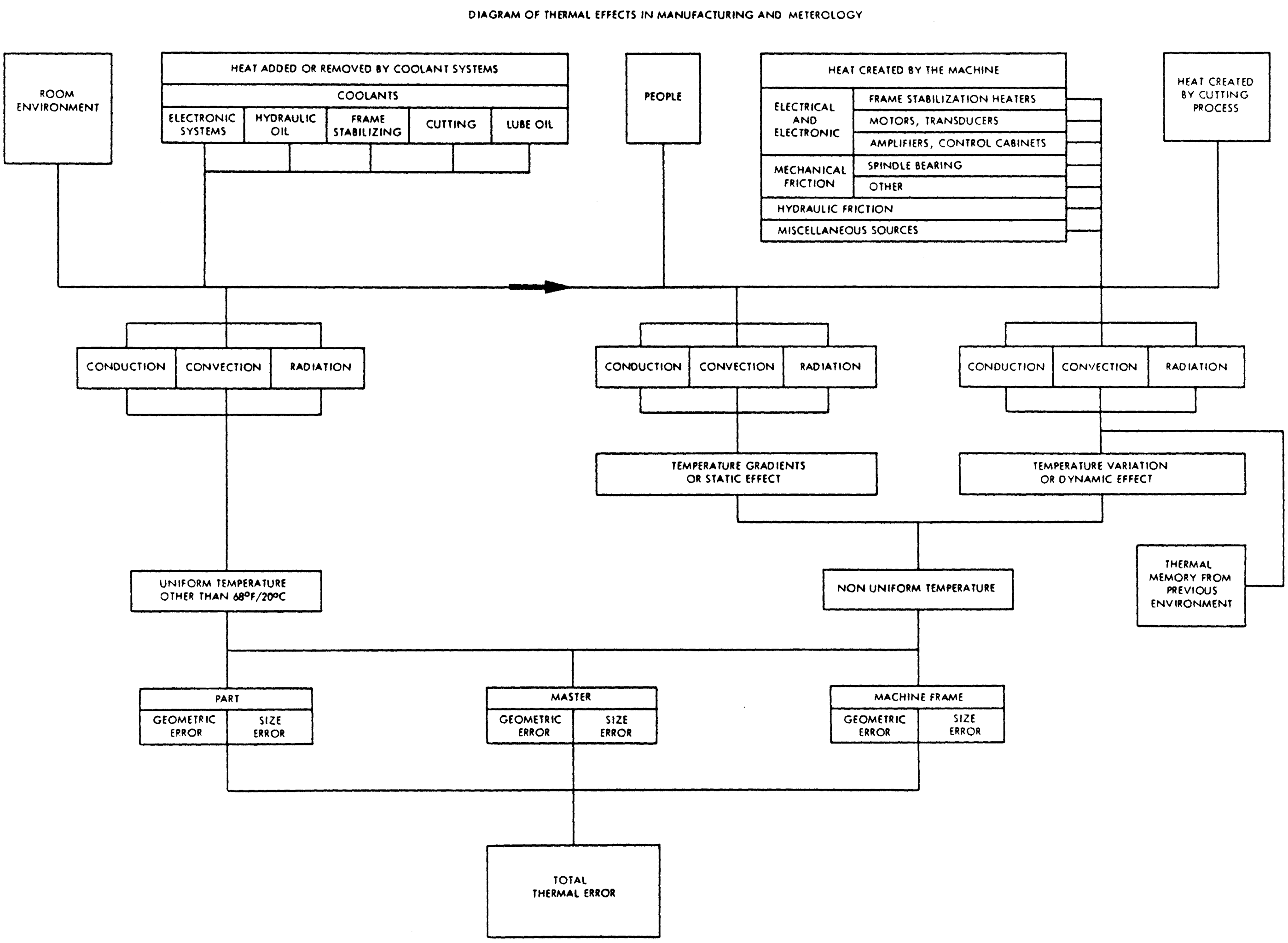

Figure 2

that can create uniform temperatures. This is illustrated by the arrow in the diagram. The remaining heat sources will cause either steady-state temperature gradients or temperature variation, or both. All sources affect the three-element system through the three possible modes of heat transfer: conduction, convection, and radiation. The errors can be either geometrical, or size. By geometrical errors we mean squareness, straightness, flatness, and angular errors developed as a result of temperature gradients or non-uniform coefficients of expansion.

Measuring machines are a special case of machine tools where there is no cutting process heat, and a minimum of spindle bearing friction heat.

PROBLEM I: UNIFORM TEMPERATURES OTHER THAN 68°F(20°C)

Discussion

Decisions concerning the average level for shop temperature control are difficult to make. Insufficient technical guidelines are available to help management in making a choice. The whole question is shrouded with emotion, misconception, and a wide variety of expert opinion. Researchers have unfortunately regarded the problem as well-known, and unworthy of further investigation.

The following excerpt from Ref. 42 will provide some background for further discussion of this topic:

> "A meter is the distance between two fixed points in space. It is presently defined as 1,650,763.73 wavelengths of the orange-red radiation of krypton-86 when propagated in vacuum. A meter does not vary with temperature and never has. This fact is obscured because the lengths of the more common representations of the meter such as gage blocks, lead screws, and scales do vary with temperature. The lengths of most of the materials we deal with also change with temperature. In April, 1931, the International Committee of Weights and Measures meeting in Paris agreed that henceforth when we describe the length of any object, whether it be a gage block or a broomstick, we automatically mean its length when it is at a temperature of 68°F(20°C).
>
> "If dimensions are only correct at 68°F, how has the world been getting by all these years by measuring at warmer temperatures? The answer is that if the work is steel and the scale is steel, the two expand together and the resultant errors tend to cancel. If, however, the work is another material, such as aluminum, the errors are different and they do not cancel. We refer to this error as 'differential expansion.'

"Knowledgeable machinists have always made differential expansion corrections. The thing that is sometimes overlooked, however, is that these corrections are not exact. Our knowledge about average coefficients of expansion is meager and we can never know the exact coefficient of each part. This inexactness is called 'uncertainty of differential expansion.'

"This inexactness or uncertainty is zero when the average temperature is 68°F, and increases according to the thermal distance from 68°F. Its magnitude varies for different materials. It is at least 5 percent for gage steel and on up to 25 percent for other materials. The coefficient of expansion of cast iron may vary as much as 4 percent between thin and thick sections. This uncertainty factor also includes the possibility of differences in expansion of a material in different directions. Differences between the actual thermal expansion and the handbook or 'nominal' expansion occur because of experimental errors and because of dissimilarities between the experimental material and the material of the workpiece."

It should be clear from the above discussion that some error will exist when measuring or machining operations are carried out at temperatures other than 68°F(20°C). The problem resolves itself into one of balancing the cost of temperature control versus the magnitude of possible error. The difficulty is that errors resulting from variations in coefficients of expansion of materials and from omissions or misapplications of differential expansion corrections are based on probability. Existence of these errors in a given case is hard to prove. The costs of maintaining 68°(20°C) shop temperatures are, on the other hand, fairly certain and usually quite sizable. Complaints from workers subjected to 68°F/20°C for the first time are also fairly certain.

In addition to making the proper choice of shop temperatures, management faces a second problem of how to make differential expansion corrections when they become necessary. According to McClure's survey of American industry[53] and opinions of the CIRP subgroup, most organizations leave the problem of differential expansion corrections up to the individual inspector or machinist. My own experience indicates that this is inadequate. The problem is particularly severe if a shop normally works with ferrous materials and corrections are not usually necessary. The habit of reading measuring instruments directly to establish dimensions is so ingrained that even the most skilled workman will often forget that corrections are necessary when dealing with non-ferrous material at temperatures warmer than 68. The responsibility involved in changing important drawing dimensions to a different value is another factor leading to the possibility that corrections will not be made. A favorite trick to avoid this responsibility is to simply record the temperature at which the measurements were made. This transfers the responsibility to someone else who may be even less qualified or willing to calculate the dimension when the part is at 68.

Present Industrial Policies

What policies are in effect in industry today regarding the 68°F(20°C) question? The need for 68°F(20°C) depends on the tolerances that are available, the coefficients of expansion of the work and the master, the size of the workpieces, and whether or not the workpiece is made of composite materials. These are the technical variables. It is becoming increasingly clear to me, however, that the human factor is the dominant one in industry at the present time. People just think that 68°F(20°C) is too cold. According to comfort charts prepared by the American Society of Heating and Ventilating Engineers, 68°F(20°C) is marginally comfortable at an air velocity of 25 ft/min (7.6 meters/min). These charts also show, however, that if the air velocity is increased to 400 ft/min (122 meters/min) the apparent temperature will be 7°F cooler. My own experience indicates that if the humidity is not too low, and if air velocities are not above 30 ft/min (9 meters/min) and if a light coat is worn, there should be no discomfort at 68°F(20°C). People who work in existing 68°F(20°C) environments do not as a rule, complain. The possibility of changing to 68°F(20°C), however, does create great concern. I personally believe that the problem is more psychological than physiological, but it is a problem.

Mottu reports that in Switzerland, a temperature of 20°C in winter and 24°C in summer has proven satisfactory for assembly of precision jig boring machines. The transition between these two temperatures is accomplished at the rate of one degree per week during fall and spring. Merchant reports that some machine tool builders in his acquaintance use 72°F (22°C) in winter and 78°F (25.4°C) in summer. Opitz is acquainted with some companies in Germany which use 66°F (19°C) in winter and 72°F (22°C) in summer. These policies are dictated by the need for economy in operating costs and comfort of personnel.

One company that I am familiar with operates its plant at a temperature of 73.4°F (23°C) for reasons of comfort and economy. This company produces a variety of close-tolerance machined parts having a very high coefficient of expansion. They have a policy of making differential expansion corrections on every drawing before it is released to the shop. A necessary assumption is that the shop temperature will be 73.4°F (23°C) at the time of measurement. This policy has been a failure, but only because of the lack of sufficiently tight temperature control around 73.4, and because of the possible 25% uncertainty of differential expansion.

What research has been done on the problem of uniform temperatures other than 68°F (20°C)? As mentioned earlier, this subject has had very little investigation. Researchers have tended to concentrate their efforts on the problem of non-uniform temperatures.

Thermal Error Index

Bryan and McClure[42] have suggested that the choice of average shop temperatures can be put on a more organized basis by using the Thermal Error Index. This index presents the estimated overall thermal error as a percentage of the working tolerance. That portion of the thermal error index which results from average temperatures other than 68°F (20°C) is determined by taking the sum of the estimated uncertainty of expansion of the part and the master, adding the value of nominal differential expansion if corrections are not made, and taking this sum as a percentage of the working tolerance of the part. For example, a 10 in. (254 mm) long aluminum part having a tolerance of 0.001 in. (25 μ) is being inspected at 72°F (22°C). A steel height gage is being used. No corrections are made. Assuming the uncertainty of coefficient of expansion of the aluminum to be 20% and the steel 10%, the index comes out to be 31%. To determine the suitability of the 72°F(22°C) environment for this case, management asks itself if it can afford to give up a possible 31% of the working tolerance to this one source of error. The index also lends itself to the adoption of a general policy of maintaining thermal error at say, 10% of the working tolerance.

The thermal error index can reveal that our intuition is often incorrect about what operations require 68°F (20°C). For example, the index for the calibration of 4 in. (102 mm) long, Class A steel gage blocks by comparison at 70°F (21°C) is about 50%. It is also 50% for a 40 in. (1020 mm) aluminum part having a tolerance of 0.005 in. (127 μ) measured at 70°F(21°C) and best effort corrections made to 68°F(20°C). This kind of thinking can be used by a shop foreman to show that his requirement for 68°F(20°C) is just as urgent as that of the metrology laboratory.

The index has the desirable feature of responding to each of the variables that affect the need for 68°F(20°C). These are: (1) amount of tolerance, (2) size of work, (3) coefficient of work and master, (4) how well the coefficients are known, and (5) whether or not differential expansion corrections are made.

Point 4 calls our attention to the benefits of more exact coefficients of expansion. Because of the significant variabilities of coefficients depending on slight changes in alloy, heat treat, etc., the only way to establish coefficients better is to measure them on each part. This suggests the need for a fast, universal, full-scale dilatometer. The need for such an instrument will be discussed at greater length in the next section.

Concerning the problem of a systematic method for making Nominal Differential Expansion corrections, N. F. Kans[17] of Ford Motor Company, Chicago, suggests the use of graphs showing the size of the part and master at different temperatures. This approach puts the responsibility for calculating corrections back in the hands of management. The workman then has specific authorization to change his readings. Kans discusses briefly the problem of uncertainty of coefficients of expansion and quotes the Tool Engineers Handbook, 1949:

> "Frequently such an error (thermal expansion) is increased by lack of definite knowledge of the particular coefficient."

Action and Research Needed

Research is needed to evaluate the magnitudes of geometrical errors resulting from different levels of uniform temperatures. Almost no information is available on this subject. Cast iron is reported to have as much as 4% difference in its coefficient, depending on the thickness of the section. If true, one would expect the geometry of precision machine tools to change significantly with changes in average temperature. Typical magnitudes are not as yet known. Investigation of this error will require an adjustable environment that has extremely close control.

Research is needed to overcome the problem of apparent human discomfort at 68°(20°). More comprehensive studies of comfort in the 66-76°F range are needed.

Cooperation with air-conditioning engineers is needed to find better ways of cooling and distributing air in shop areas at less cost. Better specifications and means of testing must be developed to insure satisfactory environmental performance for a given cost.

Research is needed to find better ways of administering differential expansion corrections, both in manufacturing and measuring. Design engineers must accept greater responsibility for thermal effects. The standard drawing notation "Temperature corrections may be made" must, in the future, be supplemented with some assistance on how to make them.

Research is needed to develop a full-scale dilatometer to permit direct measurement of coefficients of expansion of workpieces. Several means for accomplishing this have been proposed. R. K. Kirby of the U. S. Bureau of Standards suggests that temperature-calibrated strain gages be attached to the work during temperature cycling. T. R. Young, also of the Bureau of Standards, has suggested that the change of density with temperature, as measured by Archmides' immersion method, can give the volumetric coefficient of expansion. E. G. Loewen suggests that an Invar or quartz frame, large enough to accept the work, be arranged to hold an indicator against the work during temperature cycle.

Research is needed to investigate the use of coolants to flood the part, master, and machine frame with 68°F liquid during measuring or machining. A system approaching this concept is presently under construction at Lawrence Radiation Laboratory, Livermore. The long-range possibility of complete liquid submergence of part, master, and frame also needs to be explored.

Research is needed to provide improved means of measuring surface temperatures. Existing instruments are costly, bulky, and inconvenient to use. Thermistor probes offer the most advantages at the present time. They release some heat, however, and their readings are therefore dependent on the conductivity of their surroundings. Another need is for a simple means of determining an absolute 68°F(20°C) for calibration purposes. Existing thermometry procedures require interpolation between the triple point and the boiling point of water to determine 68°F(20°C). Some kind of a natural standard similar to the triple point of water is needed to provide calibration at 68°F(20°C).

PROBLEM II: NON-UNIFORM TEMPERATURES

The thermal-effects diagram, Fig. 1, shows that the three-element system, consisting of part, master and frame, is affected by steady-state and dynamic temperature differences originating from any of the six principal sources of thermal influence listed in section III.

Concept of Three-Element System

An excerpt from Ref. 52 will serve to review the concept of the three-element system:

> "The first step in any study of thermal effects is locating the three-element system from the mass of hardware of a complex machine. The part is always well-defined, but in some instances extra effort is required to separate the master and frame elements.
>
> "Consider a 1-in. indicating micrometer and three different procedures for its use:
>
> (1) "The part is 1-in. in diameter. A 1-in. gage block is used to master the micrometer before the part is measured. Here the three elements are quite distinct. The micrometer is used only as the comparator frame.
>
> (2) "The micrometer is used to measure the part size without checking zero. In this case, the micrometer frame plus screw, opened to the size of the part, constitutes the master. The same structure also fulfills the function of the comparator.
>
> (3) "Before the part is measured, the micrometer is brought to its null position and a zero correction is made. In this case, the master is that portion of the screw which is withdrawn to make room for the part. The rest of the micrometer forms the comparator.
>
> "Consider now a 2-in. indicating micrometer and the following case: The part is 1/2 in. in diameter. A 1-in. gage block is used to master the micrometer. The master in this case is the gage block plus that portion of the screw, approximately 1/2 in. long, which is withdrawn to make room for the part.
>
> "These four cases show how the master and comparator functions can be changed by changes made in the operating procedure."

By analogy to the example of the micrometer, the three-element system exists and can be located in all machine tools and gages. Further discussion of the three-element system can be found in Ref. 56.

The need for identifying the three-element system and for thinking in its terms can be appreciated by imagining the effect of a design change which would convert each one of the three elements in turn to Invar.

Before beginning discussion of the problem of non-uniform temperatures, it may be useful to mention a generalized solution proposed or implied by McClure, Schunck, Wolfbauer, and others. The proposal is that all systematic solutions (as distinguished from procedural solutions) must fall into one of the following three categories:

1. Control of heat flows into the three-element system.
2. Design of the frame and master to reduce sensitivity to heat flow.
3. Compensation through controlled relative motions within the frame or master.

Sources of Thermal Influence

The validity of this proposal can be tested in the course of the following discussions concerning the influence of various heat sources on the three-element system:

Heat produced by friction and drive motors.—This problem is the most serious and also the most investigated aspect of thermal effects. Thermal distortion of the machine frame and spindle growth, in particular, constitute some of the largest errors in any machine tool. Typical spindle growth magnitudes for lathes are 4,000 microinches (100 μ) from cold start to soak-out at full spindle speed. A comparable problem is spindle housing growth on jig borers.

Machine frame distortion can be angular as well as linear. As with many other thermal effects, machine distortions caused by friction are both dynamic and static. During warmup the effect is dynamic; after warmup, it is static. Steady-state distortion of the frame is not necessarily a complete solution because heat flows resulting from temperature gradients may, in turn, affect the part or the master, either dynamically or statically. The common practice of pre-warming a machine cannot be considered as a satisfactory solution because of the difficulties of extra wear during warmup, wastage of power, and the need to shut down the spindle to load work, change tools, measure, etc.

A large percentage of the existing thermal effects research literature is concerned with the problem of friction-induced frame distortion. The work of Wolfbauer, Peklenik, Peters, Optiz, Shunck, Mottu, Pahlitzch, Victory, and others all cover this point. A 1951 report by the Russian engineer, B. T. Breev, is outstanding because it states the problem so well at such an early date. Peters' study of straightness of travel of lathe bedways during spindle warmup complements Yoshida's work in Japan which consists of plots of temperature fields and absolute displacements with respect to the floor. Gelfeld[28] has studied straightness of travel of slideways under the influence of a hydraulic oil tank placed within the machine bed. Relatively little information is available on the influence of frictional heat on the part and master.

Solutions to the problem of frictional heat and drive motors are not as numerous as the investigations describing the problem. They can be grouped according to the three possibilities of: (1) controlling heat, (2) designing to minimize sensitivity, and (3) compensating.

Moore and Victory[6] used a combination of control of heat and design insensitivity in the Moore Jig Grinder. They selected spindle drive motors having minimum rise in temperature, cast the entire spindle housing from Invar, and then installed a patented heating device which automatically turns on when the motor is stopped.

Knyazhitskii[34] describes a compensation system for jig borer spindle housing growth which utilizes the difference in temperature between the bed and the spindle housing to generate an electrical signal which is used to zero shift the inductive measuring system on the sensitive axis. He acknowledges the difficulty of finding a location in the housing whose temperature always represents the position of the spindle.

K. Ränsch of Germany holds a patent on a device which uses Invar bars in the bed and in the spindle housing to develop a visual indication of relative movement.

Wolfbauer[33] describes a patented system used on Deckel jig borers which utilizes a high coefficient bar to actuate the reed-mounted spindle housing in a direction opposite to its thermal expansion.

The proceedings of the 1965 Aachen Colloqium describe a compensating system used by Kearney and Trecker which uses an Invar bar mounted parallel to the spindle of a horizontal milling machine to actuate a potentiometer which gives a signal representing the spindle position. This signal is used to zero shift the control system or to control a heater which keeps the spindle in a fixed position.

The Excello Corporation has designed a water-cooling system surrounding the headstock of a precision numerically controlled lathe that is capable of holding spindle growth to 80 microinches (2 μ) through a full duty cycle. J. B. Richards[43] describes the retrofitting of an air-bearing spindle to an N. C. lathe for the express purpose of controlling spindle growth. The original ball-bearing spindle had 800 microinches of growth and the new air-bearing spindle only 150 microinches. Richards also compares the thermal movement of the tool-setting station for the two spindles. Schunck[44] discusses some excellent ideas on how to reduce sensitivity of structures to thermal influence through symmetry of design.

The solutions outlined above are all in service in industry, but none of them are completely satisfactory. Residual errors are still a high percentage of the kinematic accuracy of the machine. Continuing research is needed to establish additional options for the machine tool designer.

A promising approach would seem to be further application of the techniques of prediction that have been pioneered by McClure.[42] These techniques have been used to accurately predict frame distortion caused by variations in the convective environment. When prediction has been reliably achieved, compensation should be easy.

Complete liquid submergence also needs research.

Another possibility is to simply declare that machines of high horsepower are not compatible with machines of high accuracy and proceed with the design of a new kind of finishing machine.

Previous environments.—When an object is moved to a different environment, a certain amount of time must pass before it reaches thermal equilibrium with the new environment. During this soaking time, the object may suffer temporary geometrical distortion. Size errors will also result if attempts are made to use the object as a portion of a three-element system during its soak-out period. The effect is always dynamic, and its location on the diagram in Fig. 2 reflects this fact. The part is the most likely portion of the three-element system to be moved, but there are many situations where the master is moved and a few where the frame is moved. A simple example is the case of a machinist who keeps his micrometer in his pocket.

The soak-out problem is well-known, but frequently forgotten under the press of business. It can become a critical production bottleneck in plants where parts are stored in different environments prior to machining, or where parts are inspected and machined in different areas. The additional floor space, inventory, and lead time required for the soaking procedure may be of great economic significance.

Some plants have set up a procedure of monitoring the surface temperature of parts during inspection. The practice permits recognition of the problem, but is not a real solution.

Large objects, such as granite surface plates, must soak for extended periods of time before reaching equilibrium. Opinion varies widely, however, on the amount of time necessary. McClure has made a contribution to this problem by setting up some simple tables and graphs giving the amount of time necessary for granite plates to reach equilibrium, depending on the dimensions of the plate, the initial temperature difference, and the desired final temperature difference. These relationships will be published as an Appendix to the American Standard for granite surface plates now being drafted.

Research work is needed to devise means of accelerating the time required for soak-out. High-velocity air showers may offer some improvement. Complete submergence in a fast-moving liquid would appear to be even better.

Reduction of cost of surface temperature measuring instruments will help to increase their availability and thus focus attention on the influence of previous environments.

Heat created by the cutting process.—The significance of this effect depends on the rate of stock removal. An important fact tending to minimize the problem is that the last cut is usually the only one that counts as far as accuracy is concerned. Any temperature rise in the work caused by roughing cuts will, however, have an influence on accuracy. It is common jig borer practice, therefore, to rough all holes before finishing. This is a procedural solution which works, but the price is usually some loss in efficiency.

The conditions of high volume production are quite different from jig borer practice, however. As J. Tlusty of Prague has often emphasized, the heat released from the cutting process in high production work completely dominates all other thermal effects. This fact exerts a demoralizing influence on efforts to correct other sources of error. Why worry about room temperature variation when 50 horsepower is being pumped into the workpiece?

In addition to its effect on the part, heat released from the cut affects the machine frame and the master by conduction, convection, and radiation. The primary frame effect is on the tool and its immediate supporting structure. Bryan, Clouser and McClure[54] have devised a means of measuring the growth of the tool toward the work in turning. For the one machine studied, they concluded that the effect is quite serious for dry cutting (550 microinches at 0.020 in. depth of cut and 200 ft/min) but within reason if the tool is flooded with coolant (100 microinches under the same conditions). Secondary effects on the frame are created by the warmed coolant and chips coming into contact with the bed. Opitz mentions the advantages of inclined bed lathes to prevent this contact.

Use of coolant in varying degrees has been the only solution advanced so far. There is some difference of opinion on the use of massive amounts of coolant. Mottu believes that the use of coolant is the only solution, but cautions that workmen do not like to work with too much coolant. He is also concerned with the proper lubrication of the machine if too much coolant is used. B. L. Ten Horn, of Eindhoven, has had good success with the installation of a central tank of coolant to service a number of grinders. The tank holds thousands of gallons of coolant, and the resultant capacity to store heat provides a uniform temperature without the need for temperature control. J. Loxham, of Cranfield, has used large quantities of temperature-controlled coolant on an experimental cylindrical grinder to control the heat from the cutting process. Frictional heat from the machine and the effect of room temperature variation during the day is also kept under control. The ring master used for sizing the work is normally kept submerged in the coolant.

New research is needed to evaluate the magnitude of error caused by workpiece heating. The problem may not be too severe in single-point machining of large parts with high heat capacity.

Research is needed to establish the effectiveness of complete liquid submergence versus massive amounts of conventional flow. The limit in either case would appear to be the forces exerted by the liquid flow on the part and the machine.

Research is needed to determine the economics of using a separate machine for finishing.

Another possibility requiring investigation is compensation. In this case, compensation would be accomplished by programming continuous-path, numerically-controlled machines to cut an empirically determined path that will result in a good part at 68°F. F. Broome and P. Anderson of Union Carbide, Oak Ridge, Tennessee, have published a paper[55] describing a procedure for correcting an APT part description for repeatable but non-correctable machining errors.

Temperature variation in coolant systems.—Coolants are an important solution to many thermal problems. Some machine tools now in service have coolants for five different purposes: electrical cabinets, hydraulic supply systems, lubricating oil, cutting fluid, and frame stabilization. There are no particular design problems in these systems since liquid temperature is relatively easy to control. The consequences of any malfunction can quickly put a machine out of tolerance, however. Continuous temperature monitoring of each system with convenient indication and interlocks is desirable. The use of off/on type controllers can be quite satisfactory.

Research is needed to reduce the cost and complexity of coolant temperature control.

Improved reliability is another requirement that must be met in the future.

Influence of personnel.—Every machinist and inspector has had some experience with the influence of body temperature on dimensional measurement. Heat from conduction by handling affects gage blocks, micrometers and precision setups of all kinds. Heat transfer by convection and radiation can also cause surprisingly large effects. The average heat output of the body is 100 watts. If several people are concentrated in front of a machine, their influence is readily apparent. A useful test for the thermal sensitivity of gage head brackets and arms is to concentrate three or four people near the setup for ten minutes or so, and watch for changes in readings. The effect of groups of people can be a serious problem during the testing of a new machine when curious visitors (often top management) are attracted to the area.

One solution to the problem of people is to separate them from the three-element system by means of a complete enclosure. This approach is necessary when dealing with radioactive materials. The side benefits from a thermal standpoint are quite impressive.

Another way of relieving the people problem is use of high-volume air circulation. Up to three room changes per minute can be achieved under laminar flow conditions without noticeable drafts. Convective influence under these conditions is quickly dissipated. Radiant influence is dissipated by the scrubbing effect of the air on the part, master, and frame.

Research for this problem is hard to suggest. Some effort might be directed toward the possible development of an inexpensive, light-weight shop coat that would limit the release of body heat by convection and radiation, and at the same time provide greater comfort at 68°F. Improvements in gloves would also be welcome.

<u>Heat created by electrical control and hydraulic power systems.</u>—This category of heat source is intended to include all accessory equipment that can be removed from the immediate proximity of the machine without major redesign. Control cabinets, electrical power supplies, motor controllers, tape readers, computers, hydraulic pumps, refrigeration units and heat exchangers can all be located remotely by running extra piping and wiring. It is somewhat shocking to observe that the size and cost of this accessory equipment for modern machine tools is beginning to exceed that of the machine itself. Heat losses of this equipment can exceed 100 horsepower.

Opitz is concerned with the detrimental effect of these heat sources and observes that:

> "Efforts to control thermal effects errors should, first of all, begin with a suitable design. All heat sources other than those directly connected with the cutting process should be installed outside the work area."

The Excello Corporation of Detroit has taken action along these lines by specifically recommending that large portions of the accessory equipment, including hydraulic pumps, be placed outside the room. Reduction of noise level in the shop is a fringe benefit. Excello has also provided 68°F temperature control on the hydraulic oil supply, cutting fluid supply, and headstock cooling supply.

The Sundstrand Corporation, of Rockford, Illinois, is one of the first companies to provide liquid cooling of electrical control cabinets. Prior to this development, fans were used to blow the heat into the room and more often than not, directly on to the machine.

All machine tool builders can provide these improvements if the customer is willing to pay for them. There are relatively few technical problems involved. The difficulty is that the builder must carefully explain how bad his machine will be without such improvements, and he is often unwilling to do this.

Research is needed to provide reliable means of unloading hydraulic pumps when there is no demand for oil. The current practice of using constant-volume pumps and relief valves to regulate pressure is an engineering disgrace. The wasted pumping power is bad enough, but the cost of re-cooling the oil by refrigeration is unacceptable.

<u>Temperature gradients in the room environment.</u>—Steady-state temperature differences caused by imperfect distribution of air or local heat sources exist to some degree in all rooms. Their effect on the part, master, or machine frame can result in errors of size or geometry. Granite surface plates are significantly influenced by vertical gradients. R. V. Rahn, of Dayton, Ohio, has observed repeatable differences of flatness of plates, depending on the time of year, and traced the differences to slight changes in gradients. The new American Standard for surface plates will limit the magnitude of permissable gradients according to the grade of plate.

Mottu has had considerable experience with the problem of room gradients and believes them to be a primary source of error in metrology. Measuring machines are generally arranged with the master below the work table. Vertical gradients cause bias in the measurement. Mottu holds a patent on a system for compensating for this error by tilting the scale or lead screw corrector bar, either manually or automatically, in accordance with measured temperatures of the part and master. Provision is made for dialing in different coefficients of expansion of the part. As a result, the system is also effective for making differential expansion corrections for uniform temperatures other than 68°F(20°C).

Schunck[44] discusses the effects of gradients in simple objects, as well as in complete machine tools.

High rates of air circulation are an effective means of controlling room gradients. The more pounds of air in circulation, the smaller the temperature difference between inlet and outlet for the same amount of heat removal.

Loewen has long been an advocate for fans as a supplementary means of circulating air within a room to avoid gradients. He has solved many difficult problems with this simple approach.

Research is needed to establish meaningful national standards for room gradients. Definitions, means of test, and instruments must be developed that will yield repeatable results for the same environment.

Research is needed to establish better methods of calculating the true shapes of objects having known, but non-linear, three-dimensional temperature gradients.

Temperature variation in the room environment.—Room temperature variation affects the three-element system in a way that is not readily apparent. There would be no consequence of temperature variation if all portions of the three-element system had exactly the same coefficient of expansion, the same volume to surface ratio, and the same size and shape. This is not the case in real systems. Thin sections having small volume-to-surface ratios will respond faster than thick sections. Temperature variation affects the length of every object in a different way. The exact description of this influence is called Dimensional Response. It varies as a function of frequency of temperature oscillation. The difference in response between any two objects is called Differential Response. Differential response reaches a maximum at some particular frequency of oscillation in a manner that is analogous to resonance in vibration work. The magnitude of differential response between part to master, part to frame, and master to frame determines the sensitivity that a given machining or measuring procedure will exhibit to temperature variation. Every procedure has a different sensitivity which is dependent on the length of time that elapses between mastering and measuring and on the frequency of oscillation. Geometrical as well as size errors can result from temperature variation.

Sokolow, of the USSR, has calculated[24] the geometric response of machine tool bedways to temperature variation. His technique involves the breakdown of several portions of the cross section of the bed into individual lumps. His analysis shows that a perfectly symmetrical bed would have no geometrical sensitivity.

Grand[3,7] was the first to explain the exact way in which temperature variation affects linear measurements. Most of his work was theoretical, but he conducted some experiments on a SIP measuring machine to confirm his calculations.

Bryan and McClure[42] conducted most of their investigations on this subject without realizing the existence of Grand's work. They made use of what they call a "drift check" to experimentally determine the effect of room temperature variation on the three-element system. A drift check consists of recording the readings of a differential transformer gage head introduced between the part or master and the machine frame during a representative time period; when the machine is cold. Any change in gage head readings is the result of the room environment. The drift check is a simple but powerful tool for evaluating the influence of shop temperature control on machines of any size or complexity. It can provide concrete justification for the need for improvements and can support the effectiveness of procedural solutions, such as working at night. Drift checks are used to evaluate the temperature variation portion of the Thermal Error Index discussed earlier.

Bryan and McClure suggest that the following action be taken to reduce error arising from temperature variation:

1. Shorten time between mastering and measuring.
2. Increase rate of air flow and improve its distribution.
3. Increase the frequency of temperature variation.
4. Decrease amplitude of temperature variation.
5. Redesign master and machine frame so their dimensional response is in better balance with the part.
6. Compensate the error by means of a room temperature sensor and known relationships to thermal drift.

Balancing of dimensional responses is one of the most practical approachs. The use of insulation to reduce the time constants of sensitive elements is surprisingly successful.

Manufacturers must provide dimensional response characteristics for both the masters and frames of their machines. This can be done by means of the step response tests developed by McClure. An unsolved problem is how to describe the characteristics of general purpose machines when their setups change drastically.

Research is needed to develop an effective method for determining the dimensional response of workpieces. Availability of this information with similar data for the machine frame and master will, for the first time, permit specification of room temperature variation on a rational basis. Such a capability might be built into the full scale dialatometer mentioned as a need earlier in this paper. The only additional requirements would be means for recording the shape of the growth curve during a step change from one stable temperature to another.

Better standards for room temperature control are needed. Better cooperation with air conditioning engineers is needed to decrease the cost and increase the effectiveness of future installations.

Research is needed to investigate the possibility of separate enclosure of the three element system in a fast moving gas or liquid.

Multiple benefits of some solutions. —Separate discussion of the various sources of thermal effects problems has shown that there is considerable overlap in the effectiveness of some solutions.

McClure's techniques of prediction and compensation appear to be a workable solution for frame distortion induced by friction as well as by room temperature variation.

High velocity, laminar air movement should be helpful in limiting room gradients and also in reducing soak-out time.

The philosophy of using low powered finishing machines for close tolerance work should have advantages in controlling heat from the cutting process as well as heat from friction.

Complete submergence in a moving liquid appears to have advantages in controlling almost all sources of thermal error. The problem of people is eliminated. Frame stabilization should be improved. Heat from the cutting process should be dissipated in the moving liquid. The soak-out problem should be reduced to a minimum. The problem of comfort at 68°F(20°C) environment is eliminated. Separation of electrical and hydraulic power supplies from the machine is inherent. The problem of controlling temperature gradients and variation in temperature should be a minimum in a moving liquid.

SUMMARY

This report has outlined the scope of the thermal effects problem and suggested some possible approaches for its solution. The need for a greater research effort is clear. Advancements in accuracy of machine tools will be largely dependent on advancements in this field. Thermal effects is an ideal subject for cooperative research since there has been so little work done and there are so few proprietary interests involved. It is an ideal subject for University research because of the wide range of engineering skills required. Professors Spur of Berlin, Opitz of Aachen, Peters of Louvain, Loxham of Cranfield, and Thal-Larsen of Berkeley have all taken the lead in this direction by encouraging their students to do graduate work on thermal effects. It should be safe to predict that this field will grow in importance and may eventually receive as much attention as the problem of mechanical vibration.

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