Thermometric Design Considerations for Temperature Monitoring in Machine Tools and CMM Structures

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Temperature measurement is an essential element in monitoring and studying the thermal deformation response of machine tools and CMM structures. In this context, temperature measurement is required for model verification, for control purposes and for determining the thermal contact resistance and other thermal boundary conditions. In these applications, where heat flux and temperature rise levels are relatively low, a proper thermometric design is a must to ensure accurate and precise results. This paper addresses the problem of thermometric design in the case of temperature measurement inside a solid body and on its surface. Results and recommendations regarding the interactions between neighbouring thermocouples, the effect of the distance between the thermocouple and the contact interface (i.e. the heat input surface), and the effect of heat flow along the thermocouple wires on the measurement error are presented. The issue of the effect of the unknown thickness and thermal conductivity of the surface paint on the uncertainty in surface temperature measurement is also addressed.

Keywords: Temperature measurement; Thermal contact resistance; Thermal deformation; Thermometric design; Machine tools

1. Introduction

The machining errors attributed to the thermal deformation of machine-tool structures are in many cases of an order of magnitude the same as or higher than those errors due to static and dynamic compliance. The recent demands for increased machining accuracy have renewed the momentum for further research in this field, both applied and fundamental. This was well demonstrated in the 1990 CIRP General Assembly meeting in Berlin, including the keynote paper on the international status of thermal error research [1]. Temperature measurement plays a central role, along with modelling, in any effort towards improving our predictive or control capabilities. To overcome the difficulty of on-line measurement of the actual dimensions of the workpiece under operating conditions, Ichimiya [2], Spur and Heisel [3] and Jędrzejewski [4] proposed a compensating control system which is based on establishing the relationship between displacement and temperature rise measured at some selected points on the structure, and then using the measured temperature as a control signal. In a recent publication [5], one of the authors proposed a closed-loop control strategy, in which a simulation model is calibrated in real time. This calibration is based on minimising the error between the temperature measurements at some discrete locations on the structure and the temperatures predicted by the simulation model.

It has been established by the authors [6, 7] that accurate prediction of the thermal deformation of the machine tool structure requires a previous knowledge of the correlation between the distributions of the contact pressure and the thermal contact resistance TCR along the structure joint. To establish this correlation, the authors have proposed a method for measurement of the distribution of the thermal contact resistance [8]. The low levels of the heat flux and temperature rise impose stringent constraints on the uncertainty band associated with the temperature measurement. This requirement becomes even more critical with the measurement of the thermal contact resistance in a real structural joint. A demonstration of the low level of temperature rise in a machine tool structure and the significant effect of its distribution over the wall of the structure on thermal deformation is given in Fig. 1. These results were obtained in [9] through computer simulation of the thermal deformation of a milling machine. Fig. 1(a) and (b) show two different temperature distributions which were obtained under a uniform, and a highly nonlinear thermal contact resistance distribution along the joint AB, respectively. The corresponding deformation of the right upper corner of the knee is shown in Fig. 1(c).

For the identification and correction of thermally induced errors in co-ordinate-measuring machines (CMM), Balsamo
et al. [10], and others, emphasised the importance of solving the problems associated with the location and number of temperature-sensing elements, as well as determining the uncertainty of temperature measurement.

Depending on whether the temperature measurement is taken in specimens (for TCR measurement) or on a real structure (for TCR measurement, verification of a model or control purposes), the measuring sensor is either inserted into the body or attached to the surface. Sources of errors in both cases are numerous and their effect is significant. The present paper is, therefore, devoted to the subject of thermometric design of a temperature measurement system. The emphasis is placed on the evaluation of systematic errors encountered in temperature measurement in a solid body (specimens or the wall of the structure) or on its surface.

2. Temperature Measurement in a Solid Body

2.1 Sources of Errors

The difference between the measured temperature and that which would have prevailed had no measurement been made can be attributed to the following three main effects:

1. The disturbance in the temperature field resulting from the holes drilled for the insertion of thermocouples
2. The heat conduction along the thermocouple wires
3. The errors introduced by the thermocouple wires (within or outside their tolerance limits), the extension wires, the reference point and the indicating and/or recording system

These measurement errors can be classified further into systematic and random errors. Another category of errors, which can be termed mistakes (e.g. reversed polarity) and “avoidable” errors (e.g. electric noise) can exceed the other two types combined. In the next subsection, only the systematic errors due to the first two effects, mentioned above, will be examined in detail. General comments pertaining to some of the significant random and avoidable error will only be outlined.

2.2 Thermometric Design Considerations

Electric noise is a serious concern in precise temperature measurement. This type of error, which is induced by electric field, magnetic field, crosstalk and common-mode rejection, can be avoided by properly shielding the extension wires and grounding them, twisting the wire leads and shielding individual pairs. References [11–15] are recommended for further information.

Random errors associated with temperature measurement in solid bodies are due primarily to the following:

1. The uncertainty in defining the exact location of the bottom of the hole and the location of the thermocouple effective junction within the hole. The random error $p_x$ due to the latter effect can be estimated from the diameters of the thermocouple wire $d_i$ and the hole $d_h$. For a beaded