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Inverse prediction of frictional heat flux and temperature in sliding contact with a protective strip by iterative regularization method

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ABSTRACT

In this study, an inverse algorithm based on the conjugate gradient method and the discrepancy principle is applied to estimate the unknown time-dependent frictional heat flux at the interface of two semi-spaces, one of them is covered by a strip of coating, during a sliding-contact process from the knowledge of temperature measurements taken within one of the semi-space. It is assumed that no prior information is available on the functional form of the unknown heat generation; hence the procedure is classified as the function estimation in inverse calculation. Results show that the relative position between the measured and the estimated quantities is of crucial importance to the accuracy of the inverse algorithm. The current methodology can be applied to the prediction of heat generation in engineering problems involving sliding-contact elements.

1. Introduction

The knowledge of the flash temperatures at a sliding interface is of fundamental importance for the tribological behavior of materials and has immediate application in the fields of lubrication, metal cutting, grinding and forming tools, mechanical seals, electric contacts, etc. The determination of the flash temperatures requires the knowledge of frictional heat generated on the sliding-contact interface. When two objects come into a sliding contact, nearly all the energy dissipated by friction is converted into heat, which is distributed between the two objects, influences friction and wear characteristics, and appreciably raises the temperature at the adjacent area of the sliding interface. Theoretically, the frictional heat is considered broadly as a function of sliding velocity, friction coefficient, and contact pressure. However, the establishment of the frictional heat has never been an easy task. In the past, there have been many investigations focusing on the flash temperature of a sliding contact [1–4]. However, for the result to be realistic, appropriate solutions are needed for geometric configuration and sliding criteria. The problem of sliding contact is of significant importance in yet another engineering application. In order to obtain specific technical, protecting, or decorative properties of an object, it is a common practice nowadays to deposit a thin layer of alien material, called coating, on friction elements' surface. The wear and contact characteristics of the friction couples can be largely improved by applying protective sprayed coatings and films, in particular, made of composite materials. The technological development today makes it possible to make single- or multi-layer coatings of thickness varying in the range of micrometers and millimeters. As a result, better usable properties than the surface of foundation can be achieved. Among these properties, tribological and thermal properties of both coating and foundation affect the heat generation inside them and wear intensity on the area of rubbing. Therefore, there is a need to conduct thermal analysis on these issues, especially those associated with friction processes in various machine elements on which thin coatings with alien materials are deposited, for scientific and technical purposes [5–7].

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Nomenclature

d	thickness of the strip (m)
J	functional
J'	gradient of functional
k	thermal conductivity (W m^{-1} K^{-1})
P	compressive pressure (N m^{-2})
p	direction of descent
q	intensity of the frictional heat flux (W m^{-2})
T	temperature (K)
T_0	initial temperature of the system (K)
t	time coordinate (s)
V	sliding velocity (m s^{-1})
Y	measured temperature (K)
z	spatial coordinate (m)

Greek symbols

Δ	small variation quality
α	thermal diffusivity (m^2 s^{-1})
β	step size
γ	conjugate coefficient
η	very small value
λ	variable used in adjoint problem
σ	standard deviation
τ	transformed time coordinate
ϖ	random variable

Superscripts/subscripts

K	iterative number
m	measurement position
$*$	dimensionless quantity

Inverse analysis becomes a valuable alternative when the direct measurement of data is difficult or the measuring process is very expensive, for example, the determination of heat transfer coefficients, the detection of contact resistance, the estimation of unknown thermophysical properties of new materials, the prediction of damage in the structure fields, the detection of fouling-layer profiles on the inner wall of a piping system, the optimization of geometry, the prediction of crevice and pitting in furnace wall, the determination of heat flux at the outer surface of a vehicle re-entry, earthquake study [8], and so on. Over the past decades, the studies of inverse heat conduction problem (IHCP) have offered convenient alternatives, which largely scale down experimental work, to obtain accurate thermophysical quantities in many heat conduction problems. To date, a variety of analytical and numerical techniques have been developed for the solution of IHCP, for example, the conjugate gradient method (CGM) [9–14], the function–specification method [15], the space-marching method [16], the Tikhonov regularization method [17], and the genetic algorithm [18].

The estimation of heat source strength has been the main theme of a number of studies. For example, Neto Silva and Ozisik [19] applied the conjugate gradient method to estimate the timewise varying strength of a line heat source placed at a specified location in a rectangular region with insulated boundaries. Yang [20] used the finite-difference method in conjunction with the linear least-squares scheme to estimate the strength of the temporal dependent heat source in an infinitely long bar. Niliot and Lefevre [21] adopted a parameter estimation approach based on the boundary element method to solve the inverse problem for point heat source identification. Jin and Marin [22] presented the use of the method of fundamental solutions (MFS) for recovering the heat source in steady-state heat conduction problems from boundary temperature and heat flux measurements. Lee et al. [23] applied the conjugate gradient method to estimate the unknown space- and time-dependent heat source in aluminum-coated tapered optical fibers for scanning near-field optical microscopy, by reading the transient temperature data at the measurement positions. Recently, Chen et al. [24] estimated the heat generation at the interface of cylindrical bars during friction process by using the conjugate gradient method.

The main objective of the present study is to develop an inverse analysis to estimate the frictional heat generation at the interface of two semi-spaces, where one of them is homogeneous and the other is a semi-infinite foundation with surface covered by a thin layer of coating, during transient frictional heating. An analysis of this kind poses significant implications on the study of the problems associated with sliding-contact interface mentioned earlier. However, it is well known that inverse problems are in general unstable in the sense that small measurement errors in the experimental data may amplify significantly the errors in their solutions. As a consequence, the inverse problems are ill-posed and hence they are more difficult to solve than the direct problems. In some even worse scenarios, an inverse analysis could fail if the functional rela-