PRESENTATION OF AN INSTATIONARY MEASUREMENT METHOD FOR
DETERMINATION OF THE MATERIAL PROPERTIES THERMAL DIFFUSIVITY
AND SPECIFIC HEAT

H.-J. SÖLTER
Fraunhofer-Institute for Applied Materials Research, Bremen,
(West Germany)

ABSTRACT

In order to estimate or to compute the thermal load of
materials the corresponding thermophysical properties have
to be known:

- thermal diffusivity
- thermal conductivity
- density
- specific heat

Numeric computations are often done by usage of finite element
or finite differences computer programs. These programs require
the knowledge of the temperature dependence of the material pa-
rameters thermal diffusivity and specific heat, which can be
measured by the flash diffusivity method.

INTRODUCTION

Heat protective coatings on thermally loaded materials should
have good temperature stability and low thermal diffusivity. The
aim is a decrease of heat transfer into the uncoated or coated
material. In this case it is possible to use higher operating
temperatures resulting in higher efficiency. On the other hand,
cheaper substrates can be used for coated materials or the ser-
vice life is extended, if the temperatures within the material
are decreased, and the same external temperature load is applied.

As the substrate shall be protected, the maximum temperatures
in the interface between substrate and coating must not exceed the
melting temperature of the substrate or that of one of the coat-
ings. The material strain caused by temperature gradients and phase
transitions together with the external mechanical loads can give
information, why the coating system failed. The optimization of

coating systems with respect to temperature loads is possible, if
the temperature dependence of the thermal diffusivity and the
temperature load of the material are known. The resulting temper-
ature fields are determined by finite element- or finite differ-
ences computations under variation of the thickness of the coatings
and the system of layers.

The measurement equipment and the solution of the heat transfer differential equation

Fig. 1 shows the experimental equipment for the measurement of
thermal diffusivity. It consists of water cooled heatable vacuum
chamber, xenon flash lamp with reflector (or laser), data recor-
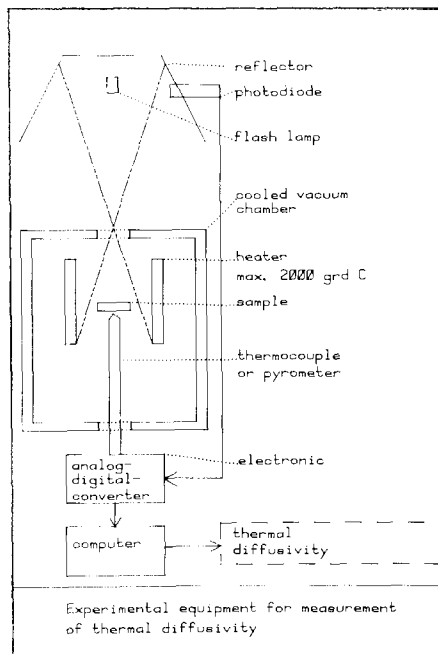ding electronics and minicomputer.

Fig. 1. Experimental equipment

The sample is heated to the chosen temperature, at which
measurements shall be performed. The samples are flat disks with
a diameter of 10 - 13 mm and a height of 1 - 2 mm. On one surface
a small temperature pulse is generated by the flashlamp or by the
laser. This temperature pulse penetrates into the sample and rises

its temperature. At the other side of the sample the temperature
increase is measured and recorded by a thermocouple or a pyrometer.

The time dependence of the temperature rise is used to deter-
mine the thermal diffusivity. The experimental equipment must be
adapted to the solution of the instationary heat transfer differ-
ential equation:

$$\partial T/\partial t \; = \; \gamma \cdot \partial T/\partial^2 x$$

T : temperature, t : time, x : displacement,
γ : thermal diffusivity

The velocity of temperature equilibrium is described by the
thermal diffusivity γ. The relation to the thermal conductivity
is $$\gamma \; = \; k/c_p \cdot \rho$$

κ : thermal conductivity, c_p : specific heat, ρ : density

The following boundary conditions are assumed for the solution
of the differential equation and the experimental equipment:

- the heat flux in the sample from one side to the other is
  in axial direction

- the entire sample surface is heated homogeneously

- the temperature rise time on the back surface of the sample
  has to be long compared to the time duration of the temperature
  pulse on the surface

- the sample is in the adiabatic state

- the heat emission from the surfaces of the sample can be
  neglected

- the sample material is homogeneous.

Measurements

The thermal diffusivities of pure nickel, armco iron, pure
copper and electrolytic copper have been investigated. Fig. 2
shows the thermal diffusivity of pure nickel (purity 99,99 %)
from room temperature up to about 1000 °C. The crosses (+) are
measured while heating, the stars (*) while cooling. The measure-
ments are in good agreement. The thermal diffusivity at room
temperature has a value of about 22 mm²/sec, then it decreases

and at about 350 °C a distinct minimum appears. This minimum is
due to the Curietemperature, at which a magnetic transition from
the ferromagnetic to paramagnetic phase occurs. From 400 °C to
1000 °C only a small increase in the value of thermal diffusivity
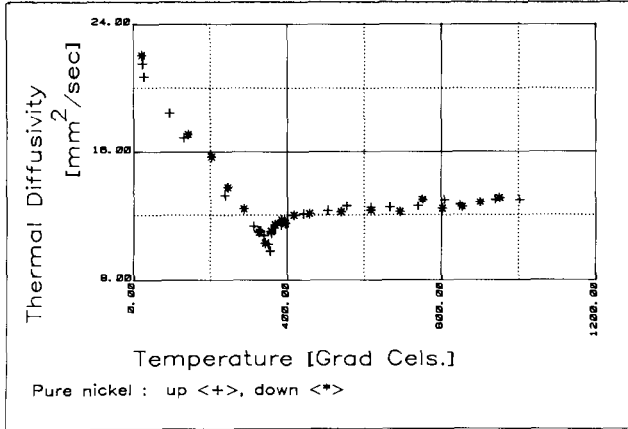was measured.

Fig. 2.   Temperature dependence of the thermal diffusivity of
          pure nickel

   Fig. 3 shows the thermal diffusivity of armco iron up to about
1000 °C. The thermal diffusivity at room temperature has a value
of about 20 mm²/sec. When the temperature increases the thermal
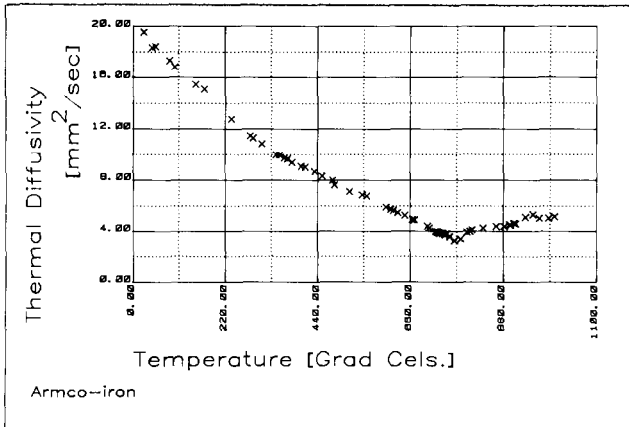

Fig. 3.   Temperature dependence of thermal diffusivity of
          armco iron

diffusivity decreases significantly (as in the case of nickel)
and at about 730 °C a minimum appears, which is again caused by
the magnetic transition. At about 900 °C a slight transient occurs.
This transient is due to the phase transition (a/γ) from ferrite
to austenite.

Fig. 4 compares two measurements of thermal diffusivity of
pure copper (purity 99.998 %) and electrolytic copper (purity
99.98 %). The temperature dependence of pure copper is shown in
the upper curve. The lower curve describes the temperature de-
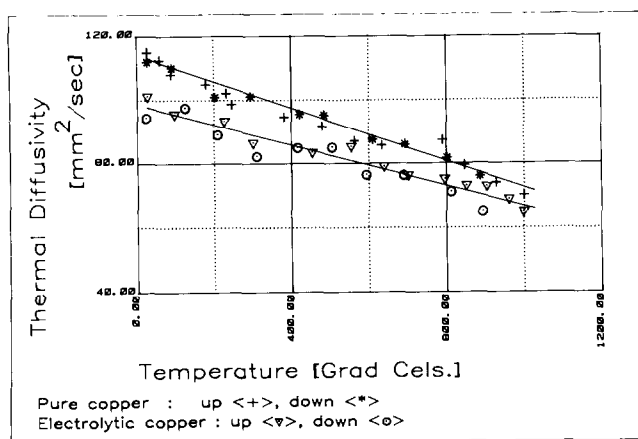pendence of electrolytic copper.

Fig. 4. Temperature dependence of thermal diffusivity of
pure and electrolytic copper

The values for pure copper (+,*) and electrolytic copper
(triangle, circle) coincide very well while heating and cooling.

Though the impurity of electrolytic copper compared to pure
copper is only unsignificantly higher, the value of thermal dif-
fusivity at 20 °C decreases by 13 %. The difference between both
materials decreases at higher temperatures, as the defect gene-
ration is increased.

Specific heat

Especially at high temperatures the specific heat is one of the
basic properties of ceramic or metallic materials, the knowledge
of which is necessary for high temperature applications. The flash
diffusivity method can be used to determine the specific heat.

Originating from the unnormalized solution of the heat transfer differential equation,

$$T(t) = (Q/\rho \cdot c_p \cdot L) \cdot (1 + \Sigma(-1)^n \exp(-n^2 \cdot \pi^2 \cdot \gamma \cdot t/L^2))$$

it is obtained as the result for long times, when the entire heat of the temperature pulse has been absorbed, and temperature equilibrium exists:

$$T_{max} = Q/\rho \cdot c_p \cdot L$$

T_{max} : maximum of temperature rise
Q : absorbed heat, ρ : density,
c_p : specific heat, L : sample thickness.

T_{max} is the maximum temperature rise of the sample. The absorbed heat Q can be determined by comparison measurement with a standard material, the specific heat of which is known. The surface of both materials must have the same reflectivity.

In this case the following equation is valid:

$$Q = (c_p \cdot \rho \cdot T_{max})_{standard}$$

$$= (c_p \cdot \rho \cdot T_{max})_{unknown}$$

The unknown specific heat can be evaluated by this equation without knowledge of the absolute temperature and the amount of heat.

The disadvantages of this method are:

- The precision at low temperature is not as high as with adiabatic calorimetric measurements.
- Difficulties of measurement in the range of phase transition.
- Measurements only on solids, not possible on powders or fluids.

The advantages are:

- Small sample mass (about 1 g)
- short measurement duration (about 100 ms)
- large temperature range
- simultaneous measurements of specific heat and thermal diffusivity.

The temperature dependent values of thermal diffusivity and specific heat can be used to compute the temperature rise in coated or uncoated materials, in order to estimate if an application under given extermal temperature load is possible.