THE APPROXIMATION FUNCTION OF THERMAL RESISTANCE ON ROUGH CONTACT SURFACES IN MULTILAYER STRUCTURES

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An experimental study has been made of heat transfer in multilayer rolled steel stacks at different pressures. An approximation function is proposed to calculate the thermal resistance of layers in contact in multilayer structures.

In order to evaluate the serviceability of multilayer structures in high-temperature media, e.g., high-pressure vessels, it is necessary to know the thermal conductivity of a multilayer wall. Owing to waviness and roughness of steel rolled stock, layer surfaces make contact at separate points, while in other places air spaces develop. Since air thermal conductivity is by several orders of magnitude less than that of steel, additional contact thermal resistances (TR) arise [1]. We determine the dependence of TR on the distance \( \gamma \) between location surfaces, which specifies the tightness of layers and is expressed in terms of contact pressure \( p \) [2]

\[
\gamma = \gamma_0 / [1 + (p/p_*)^{\alpha}] .
\]

(1)

Since the contact TR is a function of the distance between location surfaces, in the initial state at \( p = 0 \) and \( \gamma = \gamma_0 \), we have \( R_0 = R(\gamma_0) \).

Next, we search for the function approximating the contact TR versus pressure in a form similar to (1) of the function \( \gamma = \gamma(p) \):

\[
R = R_0 / [1 + (p/p_*)^{\alpha}] .
\]

Expressing the pressure in terms of the distance between location surfaces from relation (1), we obtain TR as a function of \( \gamma \) for the case \( \gamma \leq \gamma_0 \)

\[
R(\gamma) = R_0 / [1 + (p/p_*)^{\alpha} (\gamma_0/\gamma - 1)] .
\]

(2)

At exfoliation of some part of the wall of a structure caused, for instance, by a drastic change in thermal conditions, we have \( \gamma > \gamma_0 \) and the total TR of such a gap also includes the resistance of air space \( R_a \), whose thickness is \( (\gamma - \gamma_0) \). It is known that the thermal resistance of air space depends on the air thermal conductivity \( \lambda_a \) and a radiation factor \( z \) [3]:

\[
1 / R_a = \lambda_a / (\gamma - \gamma_0) + z ,
\]

whence

\[
R_a = (\gamma - \gamma_0) / [\lambda_a + (\gamma - \gamma_0) z] .
\]

Therefore, the contact resistance as a function of the distance between location surfaces may be written as follows:

\[
R(\gamma) = \begin{cases} 
R_0 / [1 + (p/p_*)^{\alpha} (\gamma_0/\gamma - 1)] & \text{if } \gamma \leq \gamma_0 ; \\
R_0 (\gamma - \gamma_0) / [\lambda_a + (\gamma - \gamma_0) z] & \text{if } \gamma > \gamma_0 .
\end{cases}
\]

(3)

The function obtained is continuous, and in order to make it smooth we equate the derivatives at the point \( \gamma = \gamma_0 \) from the left and right:

\[
R'_\gamma (\gamma - 0) = R'_\gamma (\gamma + 0).
\]

From this condition we obtain the thermal resistance \( R_0 \), corresponding to the contact surfaces at zero pressure, as a function of the initial basic distance \( \gamma_0 \):

\[
R_0 = \gamma_0 \left( \frac{p_{**}/p_0}{c\lambda_0} \right).
\]

Taking into account the expression (4), the approximation function (2) acquires the form:

\[
R(p) = \frac{\gamma_0}{c\lambda_0} \left( \frac{p_{**}/p_0}{1 + p^2/p_{**}} \right),
\]

where \( c \) and \( p_{**} \) are the desired coefficients determined from the experimental results for contact thermal conductivity. For air, \( \lambda_0 \) linearly depends on the average temperature \( T_{iav} \) in a contact zone \( i \) [3]:

\[
\lambda_0(T) = 0.0244 + 7.676 \cdot 10^{-3} \cdot T_{iav}.
\]

Experimental studies of the contact thermal conductivity of rolled sheets were conducted on multilayer stacks of specimens made of steels 10G2S1, 15KhGNMFT, and 08G25FB using a special test unit [4]. The design of the test unit provides a constant heat flux along a composite core (Fig. 1), consisting of upper cylinder 1 with heater 2, lower cylinder 3 with cooler 4 and test stack 5 of specimens. The upper and lower cylinders mount thermocouples 6, with the aid of which the stationary temperature distribution along the core was recorded at different compression of the specimens on a 10-ton press.

The temperature distribution over a flat multilayer stack under steady-state thermal conditions is described by the following formulas:

\[
T_i^C = T_1 - q \left[ R_i^C + R_0 (i - 1) + \sum_{k=1}^{i-1} R_{k} \right],
\]

\[
T_i^p = T_1 - q \left[ R_i^p + R_0 (i - 1) + \sum_{k=1}^{i-1} R_{k} \right],
\]

\[
i = 1, 2, \ldots, n + 1,
\]

where \( n \) is the number of specimens in the stack.