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

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UDC 536.2.08

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 γ between location surfaces, which specifies the tightness of layers and is expressed in terms of contact pressure p [2]

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

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 $\gamma = \gamma(P)$:

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

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

$$R(\gamma) = R_0/[1 + (p_*/p_{**})^\alpha (\gamma_0/\gamma - 1)]^c. \tag{2}$$

At exfoliation of some part of the wall of a structure caused, for instance, by a drastic chanqe 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 λ_a and a radiation factor z [3]:

$$\frac{1}{R_a} = \frac{\lambda_a}{\gamma - \gamma_0} + z,$$

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:

$$R(\gamma) = \begin{cases} R_0/[1 + (p_*/p_{**})^\alpha (\gamma_0/\gamma - 1)]^c, & \text{if} \quad \gamma \leqslant \gamma_0; \\ R_0 \dfrac{\gamma - \gamma_0}{\lambda_a + (\gamma - \gamma_0) z}, & \text{if} \quad \gamma > \gamma_0. \end{cases} \tag{3}$$

Irkutsk Research and Design Institute for Chemical Engineering. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 63, No. 2, pp. 177-182, August, 1992. Original article submitted August 15, 1991.

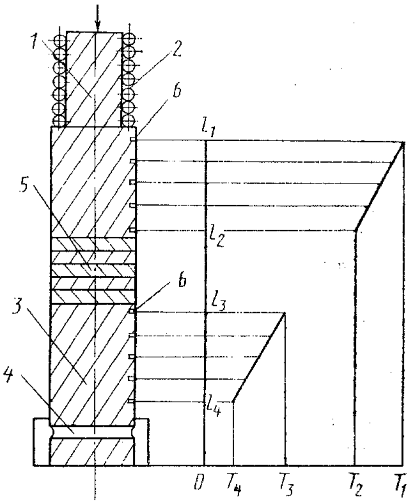

Fig. 1. Schematic of the layout of thermocouples and a multilayer stack of specimens in the central core of the test unit.

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 γ_0:

$$R_0 = \gamma_0 (p_{**}/p_*)^\alpha/(c\lambda_a). \tag{4}$$

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

$$R(p) = \frac{\gamma_0}{c\lambda_a}(p_{**}/p_*)^\alpha (1 + p^\alpha/p_{**}^\alpha)^c, \tag{5}$$

where c and p_{**} are the desired coefficients determined from the experimental results for contact thermal conductivity. For air, λ_a linearly depends on the average temperature T_i^{av} in a contact zone i [3]:

$$\lambda_a(T) = 0{,}0244 + 7{,}676 \cdot 10^{-5} \cdot T_i^{av}. \tag{6}$$

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:

$$T_i^u = T_1 - q\left[R_c^u + R_s(i-1) + \sum_{k=1}^{i-1} R_k\right];$$

$$T_i^\ell = T_1 - q\left[R_c^\ell + R_s(i-1) + \sum_{k=1}^{i} R_k\right],$$

$$i = 1, 2, \ldots, n+1,$$

where n is the number of specimens in the stack.

The heat flux is defined as the arithmetic mean in the upper and lower cylinders

$$q=\frac{1}{2}\left[\frac{\lambda_c^{u}(T_1-T_2)}{l_1-l_2}+\frac{\lambda_c^{\ell}(T_3-T_4)}{l_3-l_4}\right],$$

where T_1, T_2, T_3, and T_4 are the temperatures measured by the corresponding thermocouples (Fig. 1); l_1, l_2, l_3, and l_4 are the distances (m) from the lower edge of the core to the outer thermocouples in the upper and lower cylinders.

The average temperature for the i-th contact is as follows:

$$T_i^{av}=\frac{T_i^{u}+T_i^{\ell}}{2}=T_1-q\left[R_c^{u}+R_s(i-1)+\sum_{k=1}^{i-1}R_k+R_i/2\right], \quad i=1,\ 2,\ \dots,\ n+1. \tag{7}$$

In the contact zones of the specimen surfaces, heat is transferred by direct metal contact via the spots with thermal conductivity λ_m and air space with thermal conductivity λ_a. The total heat conduction of the i-th contact will be determined as a function of the distance γ between surfaces and relative metal contact area $\bar{S}_m$

$$\frac{1}{R_i}=\frac{\bar{S}_m\cdot\lambda_m}{\gamma}+\frac{(1-\bar{S}_m)\lambda_a}{\gamma},\quad \bar{S}_m=S_m/S_t \tag{8}$$

In thermal resistance calculations, γ must be the sum of two components, i.e., $\gamma(p)$, the distance between location surfaces and γ_m, the microroughness height, which has not been taken into account when deriving the function γ:

$$\gamma=\gamma(p)+2\gamma_m.$$

The total thermal resistance of all the contacts in the multilayer stack is:

$$R_t=\sum_{i=1}^{n+1}\frac{\gamma}{\bar{S}_m\lambda_m(T)+(1-\bar{S}_m)\lambda_a(T)}. \tag{9}$$

On the other hand, it may be determined from the experimental results as

$$R_t=(T_1-T_4)/q-R_c^{u}-R_c^{u}-R_s n. \tag{10}$$

Thus, we arrive at the set of (n + 2) equations for (n + 2) unknowns $T_1^{av}, T_2^{av}, \dots, T_{n+1}^{av}, \bar{S}_m$:

$$\begin{gathered}T_i^{av}=T_1-q\left[R_c^{u}+R_s(i-1)+\frac{0{,}5\gamma}{\bar{S}_m\lambda_m(T_i^{av})+(1-\bar{S}_m)\lambda_a(T_i^{av})}+\right.\\ \left.+\sum_{k=1}^{i-1}\frac{\gamma}{\bar{S}_m\lambda_m(T_k^{av})+(1-\bar{S}_m)\lambda_a(T_k^{av})}\right],\quad i=1,\ 2,\ \dots,\ n+1;\\ \sum_{i=1}^{n+1}\frac{\gamma}{\bar{S}_m\lambda_m(T_i^{av})+(1-\bar{S}_m)\lambda_a(T_i^{av})}=\frac{T_1-T_4}{q}-R_c^{u}-R_c^{\ell}-R_s n.\end{gathered} \tag{11}$$

Solving this system for different contact pressure values, using formulas (1) and then (8), we obtain the contact thermal resistance of a separate contact as a function of a temperature and pressure.

In multilayer-vessel calculations, it is expedient to use the averaged, for a temperature range, TR as a function of contact pressure. In this case, the contact TR is obtained by simple averaging:

$$R=R_t/(n+1).$$

Table 1 lists the results of contact TR and temperature calculations by experimental data for the steel 10G2S1 specimens: for the upper contacts (R_1, T_1), lower contacts (R_{n+1}, T_{n+1}), and averaged over all of the contacts (R, T). Microroughness has been assumed equal to γ_n = 0.015 mm.

TABLE 1. Contact TR and Temperature Values in a Multilayer Stack under Compression

Contact pressure, p	Gap · γ	$R_1 \cdot 10^3$	$R_{n+1} \cdot 10^3$	$R \cdot 10^3$	T_1	T_{n+1}	T	$\bar{S}_m \cdot 10^3$
0	0,0895	0,468	0,503	0,484	269	98	184	3,15
0,16	0,0777	0,399	0,426	0,412	262	103	183	3,23
0,40	0,0711	0,351	0,371	0,361	257	109	184	3,41
0,80	0,0649	0,296	0,311	0,303	253	116	185	3,78
1,21	0,0610	0,277	0,291	0,284	251	119	186	3,79
2,41	0,0543	0,284	0,300	0,292	250	116	183	3,18
5,18	0,0476	0,210	0,219	0,214	231	108	170	3,98
10,19	0,0427	0,176	0,183	0,179	224	110	167	4,32
20,30	0,0388	0,140	0,145	0,142	216	114	165	5,06
30,25	0,0370	0,133	0,137	0,135	219	117	168	5,11
39,81	0,0360	0,124	0,128	0,126	216	118	167	5,34

TABLE 2. Empirical Coefficients of the Distance between Location Surfaces as a Function of Contact Pressure

Steel grade	Specimen size, mm	γ_0	p_*	α
10G2S1	∅40	0,0595	1,37	0,65
	100×100	0,2165	0,108	0,645
15HGNMFT	∅40	0,037	7,68	0,525
	100×100	0,13	0,114	0,355
08G25SFB	∅40	0,056	4,114	0,56
	80×50	0,086	0,074	0,35

Contact thermal conductivity of steel 10G2Sl was investigated on 40-mm-diameter specimens. Similar specimens were used to obtain the distance γ between location surfaces as a function of contact pressure p in the form of (1) with empirical coefficients γ_0, p_*, and α, whose values are listed in Table 2. Knowing $\gamma = \gamma(p)$, we may determine the empirical coefficients p_{**} and c of the contact TR as a function of contact pressure in the form of (3)-(5) for the ∅40 mm specimens.

Now we transform the conditions (4) and equality (5) as to obtain at the known p_k and contact TR R_k a system of two equations for unknown coefficients p_{**} and c

$$p_{**} = p_* (cR_0\lambda_a/\gamma_0)^{1/\alpha},$$

$$c = \frac{1}{m}\sum_{k=1}^{m} \frac{\gamma_0}{\lambda_B R_k}\left(\frac{p_{**}}{p_*}\right)^{\alpha}\left[1+\left(\frac{p_k}{p_{**}}\right)^{\alpha}\right]^{-c}, \tag{12}$$

where m is the number of loadings.

Solving the system (12) by the iteration method, until neighboring approximations of p_{**} and c coincide with a given degree of accuracy, we arrive at empirical coefficients of the function of contact resistance versus pressure for small specimens made of all steel grades (Table 3).

Figure 2 shows the calculated dependence 1 and experimental data for small steel 10G2S1 specimens (the Y axis is to the left).

On large (100 × 100 mm) specimens, the distances between location surfaces in (1) are characterized by the following parameters: $\bar{\gamma}_0$ = 0.2165 mm; $\bar{\alpha}$ = 0.645; $\bar{p}_*$ = 0.108 mPa.

Now we determine the function of contact thermal conductivity in the form (3) for large specimens by using the experimental data for small specimens. From formula (4), it is seen that $\bar{R}_0$ is proportional to the initial distance γ_0. Therefore, for large specimens we assume $\bar{R}_0$ to be equal to:

$$\bar{R}_0 = R_0\bar{\gamma}_0/\gamma_0.$$

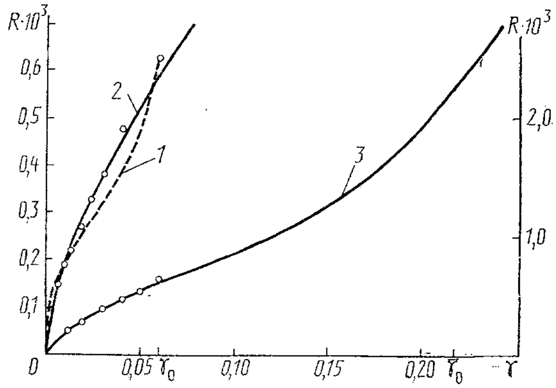

Fig. 2. Calculated dependence l and experimental data for small steel 10G2S1 specimens: 1) small specimens; 2) large specimens (right ordinate axis); 3) large specimens (left ordinate axis); points) experimental data.

TABLE 3. Empirical Coefficients of the Contact TR as a Function of Pressure

Steel grade	For small specimens			For large specimens		
	$R_0\cdot10^3$	p_{**}	c	$\bar{R}_0\cdot10^3$	$\bar{p}_{**}$	$\bar{c}$
10G2S1	0,628	0,043	0,285	2,285	0,00733	0,511
15HGNMFT	1,462	11,50	2,19	2,245	0,642	2,07
08G2SFB	1,006	4,034	0,785	3,534	0,0677	0,916

We find the unknown parameters $\bar{p}_{**}$ and $\bar{c}$ by solving the set of equations (12), in which we take $\bar{p}_*$, $\bar{\alpha}$, and $\bar{\gamma}_0$ instead of p_*, α, and γ_0. From Fig. 2 it is seen that the calculated dependence 2 for large specimens on the γ axis from zero to γ_0 coincides rather exactly with the dependence for small specimens and experimental data. Thus, the contact resistance as a function of the distance between location surfaces for large specimens is a more general dependence, which may be used to calculate multilayer structures with large contact surfaces.

Analogous results have been obtained for steels 08G2SFB and 15KhGNMFT, which are used in shipbuilding. The obtained approximation function obtained is used to evaluate the small cycle strength of multilayer high-pressure vessels operating at a high temperature and repeated loadings.

NOTATION

γ, $\gamma(p)$, distance between the location surfaces in a contact zone, mm; γ_0, $\bar{\gamma}_0$, initial distance between the surfaces at zero pressure for small and large specimens, mm; γ_m, microroughness height, mm; p, p_k, contact pressure, MPa; p_*, α, p_{**}, c, $\bar{p}_*$, $\bar{\alpha}$, $\bar{p}_{**}$, $\bar{c}$, empirical coefficients for functions $\gamma(p)$ and R(p); R, R_k, contact thermal resistance (TR), $m^2\cdot{}^\circ C/W$; R_c^u, R_c^l, R_s, TR of the upper, lower cylinders, and a specimen, respectively, $m^2\cdot{}^\circ C/W$; R_0, $\bar{R}_0$, contact TR at $p = 0$ for small and large specimens, $m^2\cdot{}^\circ C/W$; R_a, TR of air space, $m^2\cdot{}^\circ C/W$; R_t, total contact TR, $m^2\cdot{}^\circ C/W$; T_1-T_4, temperatures measured during experiments, °C; T_i^u, T_i^l, T_i^{av}, calculated temperatures at the upper and lower contact boundaries of surfaces and the average between them, °C; l_1-l_4, distance from the lower core edge to the thermocouples, m; z, heat release coefficient, W/(m·°C); q, heat flux over the composite core, W/(m·°C); λ_c^u, λ_c^l, upper and lower coefficients of thermal conductivity of the cylinder, $\lambda_a(T)$, $\lambda_m(T)$, thermal conductivity of the air space and metal spots of the surfaces at a direct constant as a function of the temperature of the contact zone, W/(m·°C); S_m, metal contact area, m^2; S_t, total area of the contact surfaces, m^2; $\tilde{S}_m$, relative metal contact area.

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