Journal of Engineering Physics and Thermophysics, Vol. 67, No. 1-2, 1994

COMPARATIVE INVESTIGATION OF THE HEAT-TRANSFERRING ABILITY OF HEAT PIPES WITH LENGTHWISE UNIFORM AND VARIABLE POROUS CAPILLARY STRUCTURES

A. G. Kostornov, N. É. Skrynskaya, and M. I. Cherkasov

UDC 536.248.2

We performed a comprehensive experimental study of low-temperature heat pipes with capillary structures having uniform and variable characteristics over their length. A comparative analysis was made, on the basis of which we formulated an approach to the optimization of a porous capillary structure with lengthwise variable parameters.

One of the means for efficient control of the working characteristics of heat pipes is the use of capillary structures in them with hydrodynamic parameters that vary over their length or thickness. Relevant published patents [1-4] quote substantial advantages of such pipes as regards the power transmitted, reliability of operation, and control of heat conduction. However, this information is basically of advertizing character, and detailed investigations are lacking in the specializd literature.

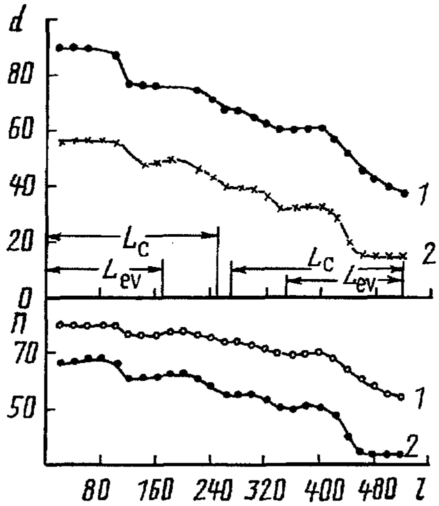
The aim of the present work was to conduct comprehensive comparative investigations of low-temperature (with water as a heat carrier) heat pipes with lengthwise uniform and variable characteristics of capillary structures.

The objects of the investigations were copper heat pipes an outer diameter of 12 mm and a length of 520 mm (the wall thickness of the container was 1 mm). Capillary structures diffusion-welded to the inner surface of the container were made of 50-μm-diameter 3-mm-long copper monodisperse fibers following the specifications TU 193-38-83. The thickness of the capillary structures in the heat pipes was kept uniform over the length and was equal to 0.6–1.0 mm. The parameters of the capillary structures, namely, the mean and maximum dimensions of the pores, the permeability, and the porosity, were determined in accordance with the State Standards GOST 26849-86, 25283-82, and 18898-89. We tested four heat pipes: two with lengthwise uniform and two with lengthwise variable capillary structures. In the first heat pipe the capillary structure porosity varied from 54 to 80% and the mean size of the pores varied from 38 to 90 μm, in the second pipe from 34 to 68% and from 15 to 56 μm, respectively. In the third heat pipe the capillary structure had the same porosity of 55% with the mean size of the pores equal to 39 μm, and the fourth pipe had 82% and 100 μm, respectively. The behavior of the parameters of the capillary structures along the lengths of the first and second heat pipes is depicted in Fig. 1.

In all of the tests the evaporation zone was equal to 170 mm, and the condensation zone varied from 200 to 250 mm. In the heat pipes with variable capillary structures heat was supplied in the zones with both higher and lower porosity.

On each heat pipe copper-constantan thermocouples with thermoelectric wires 0.15 mm in diameter were fixed uniformly along the pipe length. Heat was supplied in the evaporation zone by electric heaters switched into a 200 V circuit through a voltage regulator. The power supplied was measured by a DO57-type wattmeter (the accuracy rating is 0.5). In the zones of condensation heat was removed through a continuous-flow heat exchanger with a constant flow rate of cooling water. Its temperature at the heat exchanger inlet was kept at a level of $25\pm1^{\circ}$C with the aid of a controlled heater. The change in the cooling water temperature was measured by a differential thermocouple and monitored by the readings of mercury-in-glass thermometers with 0.01°C markings. The emf of the thermocouples was measured by an Shch68000 digital voltmeter.

Institute of Materials Science, Academy of Sciences of the Ukraine, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 67, Nos. 1-2, pp. 86-92, July-August, 1994. Original article submitted June 1, 1992.



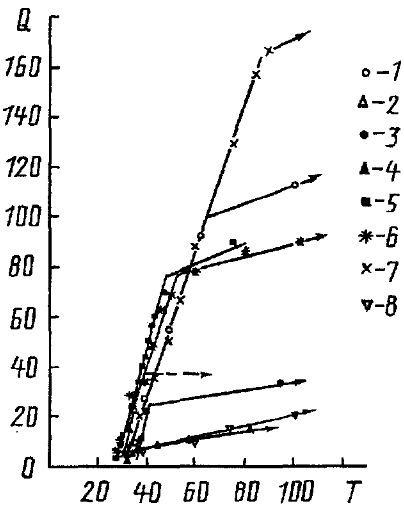


Fig. 1. Behavior of the porosity and the mean size of the pores in capillary structures with lengthwise variable parameters: 1) HP1; 2) HP2. d, μm; Π,%; l, mm.

Fig. 2. Dependence of the value of the transmitted heat flux on the temperature of the heat pipe container wall in the outer section of the evaporation zone: 1) HP1, $\theta_{ev} = 54-70\%$, $\theta_c = 74-80\%$, $L_c = 250$ mm, $\varphi = 0^o$; 2) HP3, $\theta_{ev} = \theta_c = 55\%$, $L_c = 250$ mm, $\varphi = 0^o$; 3) HP1, $\theta_{ev} = 54-70\%$, $\theta_c = 74-80\%$, $L_c = 250$ mm, $\varphi = 42^o$; 4) HP3, $\theta_{ev} = \theta_c = 55\%$, $L_c = 250$ mm, $\varphi = 45^o$; 5) HP1, $\theta_{ev} = 80-70\%$, $\theta_c = 74-54\%$, $L_c = 250$ mm, $\varphi = 0^o$; 6) HP1, $\theta_{ev} = 80-77\%$, $\theta_c = 75-54\%$; $L_c = 200$ mm, $\varphi = 0^o$; 7) HP4, $\theta_{ev} = \theta_c = 82\%$, $L_c = 220$ mm, $\varphi = 0^o$; 8) HP4, $\theta_{ev} = \theta_c = 82\%$; $L_c = 220$ mm, $\varphi = 40^o$. Q, W; T, ^{o}C.

Each heat pipe was coated on the outside by heat insulation made of basalt fibers. At each level of heat loading in a steady-state mode the heat flux supplied and the temperature field on the heat pipe surface were measured, and the heat flux removed was determined from the flow rate, heat capacity, and change in the cooling water temperature in the heat exchanger. The heat flux supplied was gradually increased until the appearance of the limit of the heat-transmitting ability of the heat pipe.

We carried out investigations of the heat-transmitting properties of the heat pipes both with pipes lying horizontally and with pipes oriented against the forces of gravity.

Based on the data obtained we determined the hydrodynamic limit of the heat-transmitting ability of the heat pipes and evaluated their thermal resistance and efficiency of operation (by the heat transfer coefficient).

Figure 2 shows the dependence of the transmitted heat flux on temperature in the outer section of the evaporation zone for heat pipes with variable and uniform capillary structures that have virtually identical characteristics in the zones of heat supply or condensation. Analysis of the figure shows the following. In the case of operation in the horizontal position and heat supply in the zone with lower porosity and smaller mean size of the pores the heat pipe HP1 with a variable capillary structure ensures the transfer of heat with a maximum heat flux, 2.7 times higher, other conditions being equal, than for the heat pipe HP3 having a uniform capillary structure and the same characteristics of the evaporation zone. The results obtained agree well with data cited for ammonia heat pipes with capillary structures with nearly identical characteristics.

In operating under the same conditions of heat supply but against the force of gravity (the excess of the evaporation zone over the condensation zone is $\varphi = 42-45^o$), the advantages of a heat pipe with a variable capillary structure are preserved, and it transmits a maximum heat flux three times higher than for a heat pipe with a uniform capillary structure.

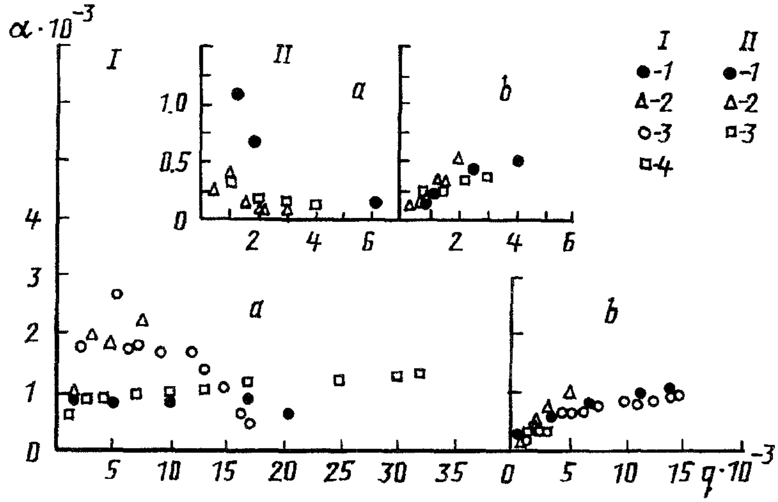


Fig. 3. Dependence of the heat transfer coefficients in the zones of evaporation (a) and condensation (b) of the heat pipes on the heat flux density (I, operation in a horizontal position; II, operation against the force of gravity): I: 1) HP1, $D^{un}_{hyd} = 38-61$ μm, $D^{un}_{hyd_c} = 7-90$ μm, $\varphi = 0^o$; 2) HP3, $D^{un}_{hyd_{ev.c}} = 39$ μm, $\varphi = 0^o$; 3) HP1, $D^{un}_{hyd_{ev}} = 90-76$ μm; $D^{un}_{hyd_c} = 68-38$ μm, $\varphi = 0^o$; 4) HP4, $D^{un}_{hyd_{ev.c}} = 100$ μm, $\varphi = 0^o$; II: 1) HP1, $\varphi = 42^o$; 2) HP3, $\varphi = 45^o$; 3) HP4, $\varphi = 40^o$. α, W/(m^2·K); q, W/m^2.

In the case of heat supply in the zone with high values of the porosity and the mean size of the pores for a horizontally oriented pipe with a variable porous structure, the maximum heat flux transmitted by this pipe is about 20% smaller than that mentioned above. The advantages of such a heat pipe, as regards the heat power transmitted, over the heat pipe HP4 with a uniform capillary structure of nearly identical parameters in the evaporation zone disappear: the maximum value of the transmitted heat flux turns out to be virtually two times lower (see Fig. 2).

The effects noted can be explained by accounting for the hydrodynamic characteristics of the structures in the zones of evaporation and condensation of the heat pipes and their influence on the processes of heat transfer.

Analyzing the dependences of the heat transfer coefficients in the evaporation and condensation zones of the heat pipes on the heat flux density (Fig. 3), we can note that the experimentally established differences in the heat-transmitting abilities of heat pipes with lengthwise uniform and variable capillary structures are mainly related to the specific features of heat transfer in the heat supply zones.

Let us consider the parameters of the capillary structures of the heat pipes investigated. In the evaporation and condensation zones of heat pipes with a uniform capillary structure the mean size of the pores is 39 μm (HP3) and 100 μm (HP4), and the maximum size is 90 and 225 μm, respectively.

In heat pipes with a variable capillary structure the sizes of the pores change in the following way: with heat supplied in the region with a lower porosity, in the zones of evaporation 38–61 μm for HP1, 15–32 μm for HP2; in the zones of condensation 70–90 μm (HP1) and 41–56 μm (HP2); with heat supplied in the region with a higher porosity, in the evaporation zones 90–76 μm for HP1, 56–48 μm for HP2; in the condensation zones 68–38 μm (HP1) and 39–15 μm (HP2). The maximum sizes of the pores in the capillary structures in the zones are equal respectively to: in the first of the indicated regimes of heat supply 145 and 205 μm (HP1); 70 and 130 μm (HP2); in the second regime 205 and 145 μm (HP1), 130 and 70 μm (HP2).

In light of the foregoing data let us analyze Fig. 3a. With heat supply to the less porous region of HP1 the minimum effective size of the pores ensuring the maximum capillary pressure is found in the outer section of the evaporation zone. Under these conditions, which are most favorable for heat pipe operation, the heat transfer coefficient is virtually independent of the heat flux density (within the limits investigated), i.e., heat is transferred by means of heat conduction through the capillary structure and by evaporation of the working liquid into a vapor channel by analogy with heat transfer of a heating surface coated with a low-porosity structure soaked with a heat-transfer agent [5]. In this case the figure of merit of the contacts between the capillary structure and the internal surface of the container over the zone of evaporation is equal to ≥0.9 of the ideal one [6]. With a heat pipe oriented against the force of gravity, this capillary structure can operate at inclination angles of up to 33–39° without drainage, whereas the limiting angle of inclination at the capillary pressure reliazed is equal to 60°.

As the effective size of the pores in these estimates [7] we used the largest and smallest maximum diameters of the pores in the evaporation zone, equal to 145 and 85 μm, as well as the largest effective diameter of the pores in this zone, equal to 61 μm.

As is seen from Fig. 3a (I and II), experimental data confirm efficient operation of the evaporation zone in a heat pipe with a variable capillary structure. It does not experience capillary limitations on the heat-transmitting ability.

Although the heat pipe with a uniform capillary structure HP3 has virtually the same determining parameters in the evaporation zone, the processes of heat transfer in it are of quite a different character. A more uniform and heat-conducting porous structure of the evaporation zone at the same value of capillary pressure ensures more intense heat transfer in a horizontally oriented heat pipe. However, in this case one observes a drop in the hydrodynamic limit of the heat-transmitting ability. This drop is equivalent to the reduction in permeability caused by decrease in porosity: in the adiabatic and condensation zones the porosity of the capillary structures amounts to 70–80% (HP1) and 55% (HP3), while for materials made of 50-μm-diameter the permeability is proportional to the porosity to the fourth power [8].

In the case of heat supply to the zone of higher porosity in a heat pipe with a variable capillary structure heat exchange processes in it are sharply enhanced (see Fig. 3a). This is due to the following two basic factors. It is known that the free surface of a porous body is related to the porosity by an extremal dependence, and for fibrous materials the maximum lies in the region of porosities of 70% [7]. Consequently, under the indicated conditions of the operation of the heat pipe the heat transfer surface of the capillary structure in the evaporation zone is close to the maximum. At the same time, although the quality of the contacts between the capillary structure and the heat pipe container will decrease, nevertheless it will not be lower than 0.87 of the ideal one [6]. Moreover, due to the enlargement of the pores (the maximum diameter of the pores increases by a factor of 1.4) the transition from the evaporative mode of heat pipe operation to boiling becomes easier due to a decrease in the mean temperature difference of this transition. The dependence of the heat transfer coefficient on the heat flux density in Fig. 3a confirms this analysis and has a form characterizing heat transfer of a surface covered with a highly porous capillary structure saturated with a heat carrier when the critical heat flux density is attained and transition to film boiling occurs [5].

Efficient evaporation of the heat carrier and accumulation in a condenser with a lower porosity and pore size decrease the velocity of its return to the zone of heat supply. The heat pipe operates in a mode characterizing a thermal diode. A decrease in capillary head (the effective size of the pores in the outer section of the evaporation zone increases by a factor of 2.4) causes a substantial decrease in the efficiency of heat transfer during heat pipe operation against the force of gravity, and already at angles of inclination of 15–17° the hydrodynamic limit of the heat-transmitting ability is equal to 35 W.

A heat pipe with a highly porous uniform capillary structure, investigated for comparison, begins to operate in the bubble boiling regime, similar to pool boiling on a smooth surface, already at small heat flux densities within the entire range of heat loadings investigated.

Due to the higher porosity of the capillary structure along the entire length of the heat pipe, i.e., the lower hydraulic resistance, the hydrodynamic limit of its heat-transmitting ability turns out to be much higher than in the heat pipe with a variable capillary structure (see Fig. 2). At the same time the efficiency of heat transfer in the zone of evaporation in the case of operation against the force of gravity corresponds fully to the realizable value of capillary pressure.

Heat transfer in the zone of condensation of all the heat pipes under all experimental conditions is virtually identical, since the determining parameters of the capillary structures are optimum or close to such: at a practically identical thickness of the capillary structures within the limits of a specified change in the porosity the quality of

TABLE 1. Comparison between Measured and Predicted Values of the Maximum Heat-Transmitting Abilities of Heat Pipes with Different Characteristics of the Porous Capillary Structures

Type of heat pipe	Angle of inclination to the horizonal, deg	Hydrodynamic limit of heat-transmitting ability, W	
		experiment	prediction
HP1	0	100	87
	42	22	18
HP2	0	20	27
HP3	0	37	30
	45	8	12
HP4	0	167	178

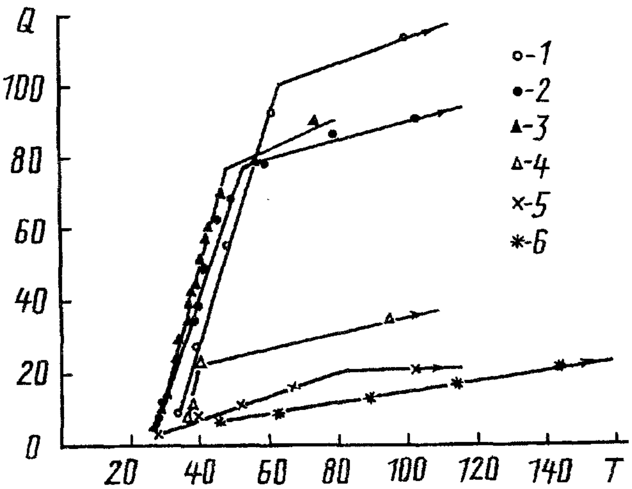


Fig. 4. Comparison of the heat-transmitting ability of heat pipes with different characteristics of the lengthwise variable capillary structures: 1) HP1, θ_{ev} = 54–70%, θ_c = 74–80%, L_c = 250 mm, $\varphi = 0^{\circ}$; 2) HP1, θ_{ev} = 80–77%, θ_c = 74–54%, L_c = 200 mm, $\varphi = 0^{\circ}$; 3) HP1, θ_{ev} = 80–77%, θ_c = 74–54%, L_c = 250 mm, $\varphi = 0^{\circ}$; 4) HP1, θ = 54–70%, θ_c = 74–80%, L_c = 250 mm, $\varphi = 42^{\circ}$; 5) HP2, θ_{ev} = 34–50%, θ_c = 56–68%, L_c = 250 mm, $\varphi = 0^{\circ}$; 6) HP2, θ_{ev} = 68–61%, θ_c = 55–34%, L_c = 200 mm, $\varphi = 0^{\circ}$.

the contacts between the structure and the container, which determines the transition thermal resistance, lies within the limits of 0.86–0.92 [6] of the ideal one, the relative value of the free heat transfer surface (its ratio to the overall surface of the porous capillary structure) is equal to 55–70% [7], and the relative thermal conductivity of the structure (its ratio to the ideal thermal conductivity of the substance with the same porosity) to 31–40% [9].

In [10] the possibility of predicting the maximum heat-transmitting ability of heat pipes with porous capillary structures is shown, which makes it possible to determine analytically the hydrodynamic limit from data on the structural-hydraulic characteristics of the porous structure, the thermophysical properties of the heat carrier, the geometric dimensions of the pipes, and the conditions of their operation.

Table 1 lists results of calculations in comparison with data obtained experimentally. It is indicative that for heat pipes with variable capillary structures satisfactory agreement between the data is observed, provided that as determining hydrodynamic parameters one takes the values of the latter that limit the heat carrier transport. In the case of heat supply to the zone of lower porosity these parameters are the effective size of the pores and the porosity at the boundary between the evaporator and the transport zone. When heat pipes operate in the mode of a thermal diode (heat supply to the zone of higher porosity), determination of the quantitative values of the structure characteristics, which vary over the length of the pipe and which justifiably determine the capillary transport, does not seem possible at the present time.

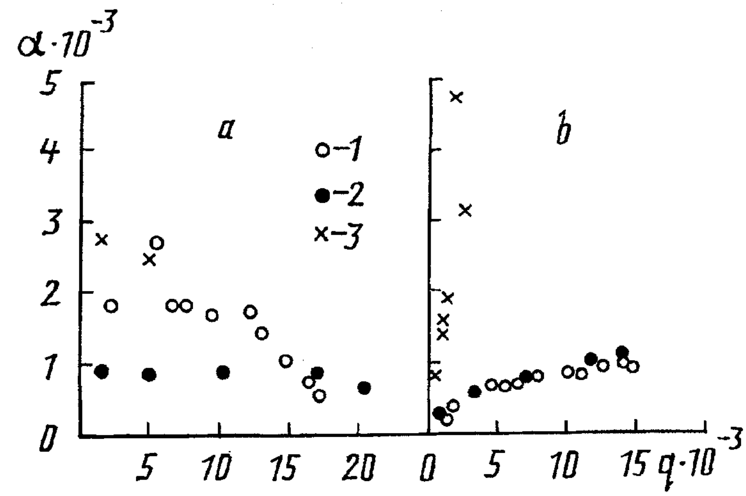


Fig. 5. Comparison of the heat transfer coefficients in the zones of evaporation (a) and condensation (b) of heat pipes with variable capillary structures: 1) HP1, $D^{\text{un}}_{\text{hyd}_\text{c}} = 38-61$ μm, $D^{\text{un}}_{\text{hyd}_\text{c}} = 70-90$ μm, $\varphi = 0°$; 2) HP1, $D^{\text{un}}_{\text{hyd}_\text{ev}} = 90-76$ μm, $D^{\text{un}}_{\text{hyd}_\text{c}} = 68-38$ μm, $\varphi = 0°$; 3) HP2, $D^{\text{un}}_{\text{hyd}_\text{ev}} = 15-32$ μm, $D^{\text{un}}_{\text{hyd}_\text{c}} = 41-56$ μm, $\varphi = 0°$.

Comparison of the heat-transmitting properties of heat pipes with porous capillary structures having lengthwise uniform and variable characteristics shows that the merits of the latter are not uniquely determined. This also follows from a comparison of the results of investigation of the characteristics of such heat pipes having substantially differing parameters of the capillary structures (see Fig. 1).

With a decrease in the porosity in all the zones the maximum heat-transmitting ability decreases sharply (practically in proportion to the fourth power of the ratio of the porosities in the evaporation zones) (Fig. 4). An increase in the capillary pressure and correspondingly in the rate of heat carrier supply to the zone of heat input and an increase in the uniformity and thermal conductivity of the capillary structure enhance the processes of heat transfer substantially (Fig. 5), but their implementation requires higher temperatures due to a decrease in the size of the pores.

Proceeding from the data obtained and their analysis, it is possible to formulate the following approach to the optimization of a porous capillary structure with lengthwise variable parameters. With technological provision of minimum thermal resistance at the boundary between the capillary structure and the internal wall of the container, the porosity in the zone of condensation should correspond to the maximum value of a free surface. In accordance with the diameter of the initial fibers, this porosity lies within the range 60–70%. The porosity of the capillary structure in the zone of heat input is selected proceeding from the necessity of providing the needed capillary pressure at a prescribed orientation of the heat pipe. In this case the effective size of the pores in the zone of evaporation should be smaller than or, in the limit, equal to the size in the condensation zone.

NOTATION

φ, angle of inclination to the horizontal; θ_{ev}, porosity of the capillary structure in the zone of evaporation; θ_c, porosity of the capillary structure in the zone of condensation; L_{ev}, length of the evaporation zone of the heat pipes; L_c, length of the condensation zone of the heat pipes; $D^{\text{un}}_{\text{hyd}}$, mean hydraulic diameter of the pores.

REFERENCES

1. Patent 1275946 (UK), Apparatus for Conduction of Exchange of Heat, Cl. F4U (1972).
2. Patent 3754594 (USA), Unidirectional Heat Exchanger, Cl, F28D (1973).

3. B. D. Markus and D. K. Edwards, Wärmerohrdocht mit abgestuften Porenabmessungen: Offenlegungsschrift 2623243 (FRG), Cl. F28D (1976).
4. Patent 4108239 (USA), Heat Pipe, *Cl.* F28D (1978).
5. M. G. Semena, A. N. Gershuni, and V. K. Zaripov, Heat Pipes with Metal-Fiber Capillary Structures [in Russian], Kiev (1984).
6. A. G. Kostornov and L. G. Galstyan, Poroshk. Metallurg., No. 5, 34-40 (1983).
7. A. G. Kostornov, Permeable Metallic Fibrous Materials [in Russian], Kiev (1983).
8. A. G. Kostornov and M. S. Shevchuk, Poroshk. Metallurg., No. 9, 77-82 (1973).
9. A. G. Kostornov and L. G. Galstyan, Poroshk. Metallurg., No. 3, 88-92 (1984).
10. A. G. Kostornov, Poroshk. Metallurg., No. 12, 43-50 (1984).