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Effect of the Size of A5N Cylindrical Aluminum Specimens on the Cooling Kinetics

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Abstract

The results of the study of "The influence of the size of cylindrical samples of A5N aluminum on the time and the rate of their cooling" are reported. According to experimental data, the temperature dependence of the heat transfer coefficient for pure metals is calculated. It has revealed that the process of cooling of the aluminum and its alloys has a relaxation behavior. It was found that the main mechanisms of natural air cooling are convection heat transfer and radiation. The characteristic cooling time due to radiation is less due to convection. The contribution of thermal radiation is noticeable at high temperatures. It was found that the characteristic times of cooling due to radiation and convection increase with increase in volume to area ratio of the sample.

Keywords: A5N aluminum, Cooling, Convection, Thermal radiation, Size effect, Temperature dependence

Introduction

Modern materials must combine high properties and qualities to ensure that the necessary service life and reliability of the products of aerospace technology, shipbuilding, mechanical engineering, nuclear energy, radio engineering and computer technology and construction [1-6]. Due with this, the production and use of pure aluminum is of particular word choice importance and its alloys, which have high mechanical strength and ductility, low density, high corrosion and heat resistance, vacuum resistance and a number of other specific characteristics [7-11].

Aluminum alloys are widely used in mechanical engineering as a material for machine parts and mechanisms for various purposes - from household appliances to aircraft [12-18]. However, many machines and mechanisms are subject to significant loads: Shock, temperature cycling, vibration, etc. Given the above, when designing parts and mechanisms, it is necessary to comprehensively study the physicochemical and dimensional properties of the properties of these alloys. The development of scientific and technological progress in aluminum production in recent years in the world market is taking place in a competitive environment. The main requirement in this case is a steady increase in the efficiency of the final product. The main direction in metallurgy in conditions of the crisis is the development of the aluminum industry, which are determined tendencies of increase in the general structure of production of high-quality products. In addition to silicon and its alloys, the most demanded product in the world market and mechanical engineering is the consumption of high-purity aluminum and its alloys as promising non-ferrous metals. From aluminum, products are obtained in the form of rolled products, ingots, packaging materials, profiles, which ultimately satisfy the needs of the consumer [19-22].

On the other hand, the combination of physical, mechanical and chemical properties of aluminum determines its wide application in almost all areas of technology, especially in the form of its alloys with other metals. In electrical engineering, aluminum successfully replaces copper, especially in the production of massive conductors, for example, in overhead lines, high-voltage cables, switchgear bus bars, transformers (the electrical conductivity of aluminum reaches 65.5 % of the electrical conductivity of copper, and it is more than 3 times lighter than copper; with a cross section, providing the same conductivity, the mass of aluminum wires is half that of copper wires) [23,24]. Ultra-pure aluminum is used in the manufacture of electrical capacitors and rectifiers, which rely on the aluminum oxide film's ability to conduct electric current in only one direction. Ultra-pure aluminum purified by zone melting is used for the synthesis of AIII BV type semiconductor compounds used for the production of semiconductor devices [25-27].

The development of non-ferrous metallurgy mainly depends on the degree of knowledge of their physicochemical and thermal properties. At present, many structural aluminum alloys have been developed with their own special physicochemical and dimensional characteristics, including ultra-light alloys with a certain specific gravity and light aluminum alloys, which are widely used in aviation, the (not required) nuclear industry, rocket and space technology, as well as in electronics and electrical engineering, both in the form of structural, and in the form of sound-absorbing and sound-proof materials [28-30].

The thermo physical properties of metals and alloys are the most important physical characteristics that determine the patterns of their behavior under various operating conditions [12,31-40]. The main interest in metal alloys is primarily due to their widespread use as part of composite alloys in various branches of technology and industry.

The thermo physical properties of aluminum alloys, depending on their alloyed structures, as well as on their (not needed) shape and size, are the subject of intensive study in recent years [34,38,39,44]. The range of their possible applications is practically unlimited and is expanding every day in various industries due to their low density, high specific strength and other excellent properties [31-33].

Previously, the thermo physical properties of pure metals alloyed with REM and AEM aluminum alloys were studied [34-38]. In all these works, the cylindrical specimens had a constant size (diameter d = 1.6 cm and height h = 3.0 cm). The study of the mechanical properties of metals and alloys by the authors [39-44] shows that the results obtained in the laboratory for samples of small sizes and for samples used in technology do not coincide in most cases. There is practically no data in the literature on the influence of the sample size on its thermal characteristics.

At present, the theory of the dependence of the cooling time on the size of the samples has not been developed. Therefore, the accumulation of experimental data on the effect of sample size on the process of heat transfer with natural heat removal is relevant and timely. The purpose of this work is to study the effect of the size of cylindrical samples of A5N aluminum on the kinetics of their cooling and to elucidate the mechanism of heat removal. The purpose of this work is to study the influence of the dimensions of cylindrical samples of A5N grade aluminum on the kinetics of their cooling and to elucidate the mechanism of heat removal. The solution to this problem can contribute to the creation of materials with predetermined properties.

Materials and methods

Samples of high-purity aluminum grade A5N (99,999 %) were chosen as objects of study.A5N grade aluminum samples were obtained at the Laboratory of Corrosion-Resistant Materials of the Institute of Chemistry named of I.N. Nikitin of the National Academy of Sciences of the Republic of Tajikistan and the State Scientific-Experimental and Production Institution of the National Academy of Sciences of the Republic of Tajikistanon the principles of zone melting, which consists in the repeated passage of the molten zone along [45] an aluminum ingot.

According to the value of the distribution coefficients $k = C_s/C_l$ (where C_s is the concentration of impurities in the solid and C_l - in the liquid phase), which largely determine the efficiency of purification from impurities, these impurities can be divided into 3 groups. The first group includes impurities that lower the melting point of aluminum; they have $k < 1$, during zone melting they concentrate in the melted zone and are transferred by it to the final part of the ingot. These impurities include Ga, Sn, Be, Sb, Ca, Th, Fe, Co, Ni, Ce, Te, Ba, Pt, Au, Bi, Pb, Cd, In, Na, Mg, Cu, Si, Ge, Zn. The second group includes impurities that increase the melting point of aluminum; they are characterized by $k > 1$ and during zone melting they are concentrated in the solid (initial) part of the ingot. These impurities include Nb, Ta, Cr, Ti, Mo, V. The third group includes impurities with a distribution coefficient very close to unity (Mn, Sc), which is practically impossible to remove during zone melting of aluminum.

The content of impurities in the original A5N obtained by the zone melting method is not more than 0.0005 % in total: lithium is less than 0.0000005; boron 0.00001; sodium less than 0.00005; magnesium less than 0.00002; potassium 0.000005; calcium 0.00003; titanium 0.00002; chromium 0.000001; manganese 0.00001; iron 0.0002; cobalt 0.000001; nickel 0.000002; copper 0.0001; zinc 0.000005 [46].

After obtaining high-purity aluminum of the A5N grade, the investigated solid samples were made, having a cylindrical shape, 3.368 cm high and 1.5 cm in diameter; 2.0, 2.5, 3.0, 3.5 and 4.0 cm. The choice of research objects is due to the possibility of using these alloys in various fields of science and technology.

For purely physical reasons, observation of monotonous change in the temperature of an object during the heating is extremely difficult due to the presence of many factors (voltage in the power supply network, the thermal conductivity of the environment, etc.). The most convenient and simple method is to use the ‘cooling-mode’ regime, which makes fewer errors during the experiment.

The specific heat capacity of materials is measured using the setup shown in **Figure 1**. The device consisted of the electric furnace (1) mounted on a bench, which can move to the horizontal direction. The sample (2) with this is a cylindrical form (h = 3.368 cm, D = 2.0, 2.5, 3.0, 3.5 and 4.0 cm), with a drilled channel at one end, into which thermocouple (3) inserted (**Figure 1**). The ends of the thermocouple are connected to the Digital Multimeter UT71B 4 m, which allowed the direct recording of the measurement results on a computer (7) in a table view. The principle of operation of the installation for measuring the temperature of a sample by cooling time is described in detail in [35,47]. The relative error of temperature measurement in the range from 400 to 4000 °C was ± 1 %, and in the range from 4000 to 10000 °C ± 2.5 %. Subtract the ambient temperature $\Delta T = T - T_0$ from the measured sample temperature. Next, we plot the dependence of the temperature difference between the sample and the environment on time: $\Delta T = f(\tau)$. All processing of the measurement results was carried out on a computer using the Microsoft Office Excel program, and the graphs were built and processed using the Sigma Plot 10 program.

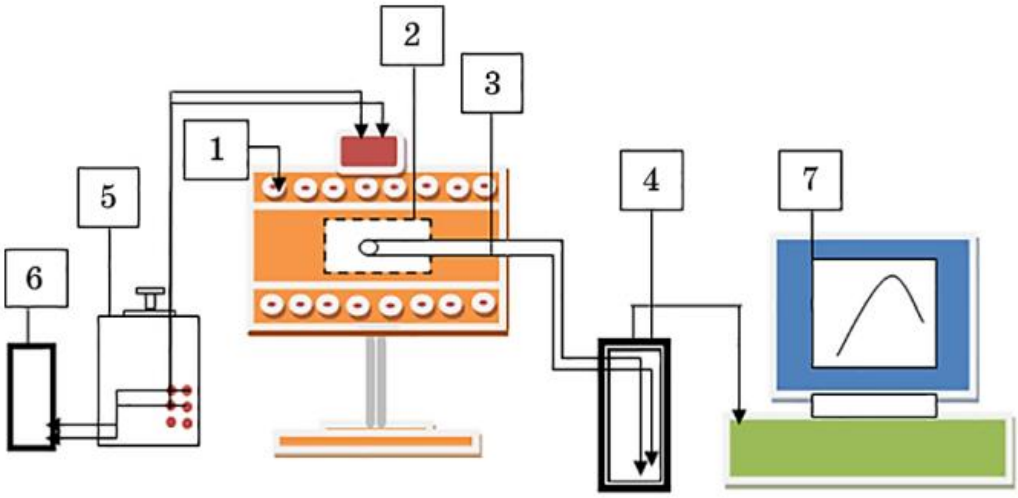

Figure 1 Experimental setup for determining the heat capacity of solids in the “cooling” mode, (1) electric furnace, (2) sample, (3) thermocouple, (4) Digital Multimeter UT71B, (5) AC voltage controller, (6) Digital Multimeter DI 9208 and (7) computer.

The cooling method was chosen to study the kinetics. The specific heat capacity of alloys in a wide temperature range was measured according to the Newton-Richmann cooling law. A body having a temperature above ambient will be cooled, and the cooling rate depends on the heat capacity of the body C and heat transfer coefficient α. The amount of heat lost by a preheated body of mass m when it is cooled by dT degrees will be:

$$dQ = CmdT \tag{1}$$

Loss of energy occurs through the surface of the body. Therefore, we can assume that the amount of heat lost through the surface of the body over time will be proportional to time, surface area S, and the difference in body temperature T and the environment T_0:$dQ_s = -\alpha(T - T_0)Sd\tau$. If the body releases heat in such a way that the temperature of all its points changes identically, then equality will be true [37]:

$$CmdT = -\alpha(T - T_0)Sd\tau \tag{2}$$

Heat transfer from a warmer body to a less warmed one is a tendency to establish thermodynamic equilibrium in a system consisting of many particles called a relaxation process. The relaxation process in time can be described as an exponential dependency. In our case, a heated body transfers its heat to the environment (i.e. a body with an infinitely large heat capacity). Therefore, the ambient temperature can be considered constant (T_0).

Results and discussion

In this work, the cooling method is used to study the dependence of the temperature of cylindrical samples of A5N aluminum of various diameters and the same height on time in a wide temperature range. The experimentally obtained time dependences of the temperature of the samples are described with a fairly good accuracy by an equation of the form [35]:

$$\Delta T = \Delta T_1 e^{-\tau/\tau_1} + \Delta T_2 e^{-\tau/\tau_2} \tag{3}$$

where, ΔT_1, ΔT_2 - temperature difference between the heated sample and the environment at the start of measurements, τ_1 and τ_2 - cooling constant for the first and second heat transfer processes.

Formula (3) shows that heat is transferred to the environment simultaneously in 2 ways and the amount of heat transferred is proportional to the surface area of the sample, the temperature difference between the body and the environment, and the corresponding heat transfer coefficient for any heat transfer mechanism.

Differentiating (3) we obtain a formula for calculating the cooling rate:

$$\frac{dT}{d\tau} = -\frac{\Delta T_1}{\tau_1} e^{-\tau/\tau_1} - \frac{\Delta T_2}{\tau_2} e^{-\tau/\tau_2}. \tag{4}$$

As an example, in **Figure 2** shows the dependence of the temperature of a sample of A5N aluminum with a diameter of 1.5 cm on the cooling time.

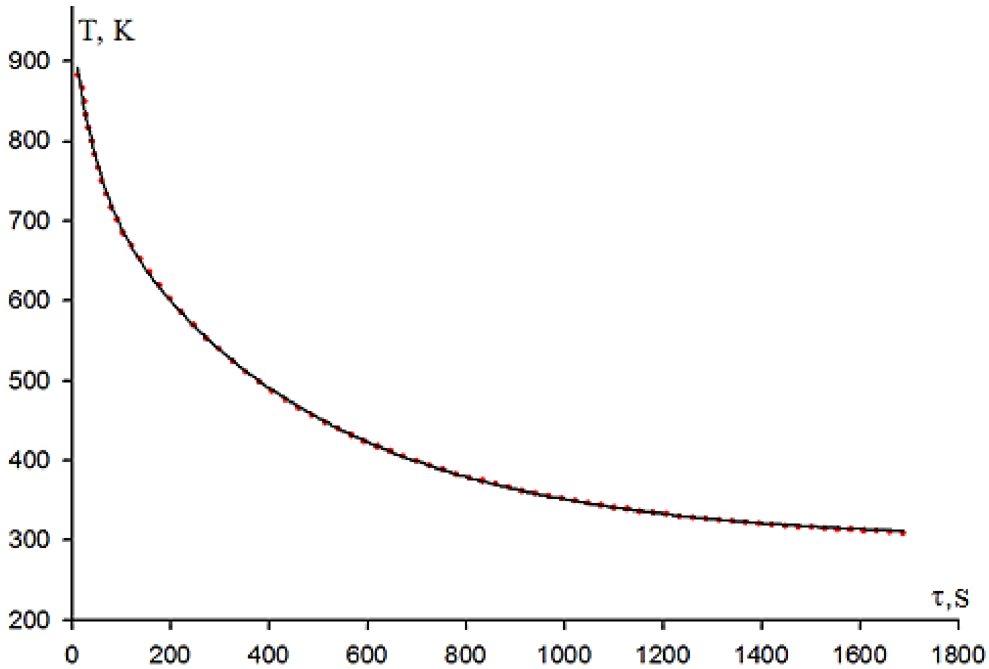

Figure 2 Dependence of the temperature difference of a cylindrical sample of A5N aluminum with a diameter of 1.5 cm and the environment on the cooling time.

As an example, in **Figure 2** shows the dependence of the temperature of a sample of A5N aluminum with a diameter of 1.5 cm on the cooling time.

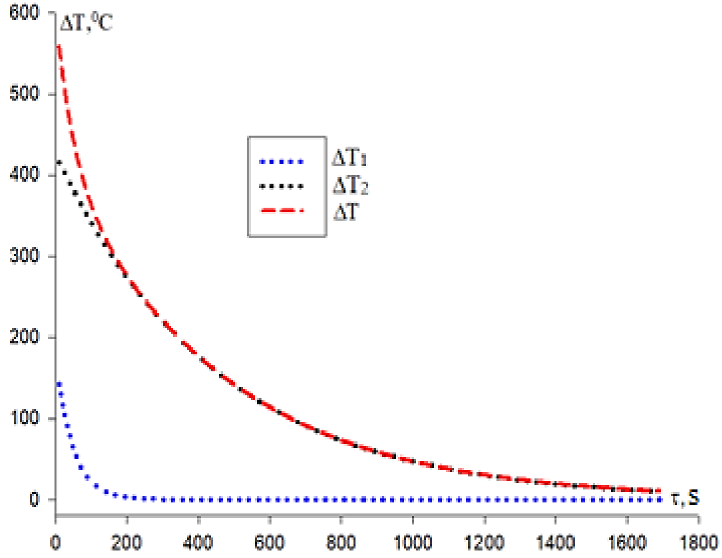

Figure 3 Dependence of sample temperature on cooling timefor aluminum brand A5N with a diameter of 1.5 cm.

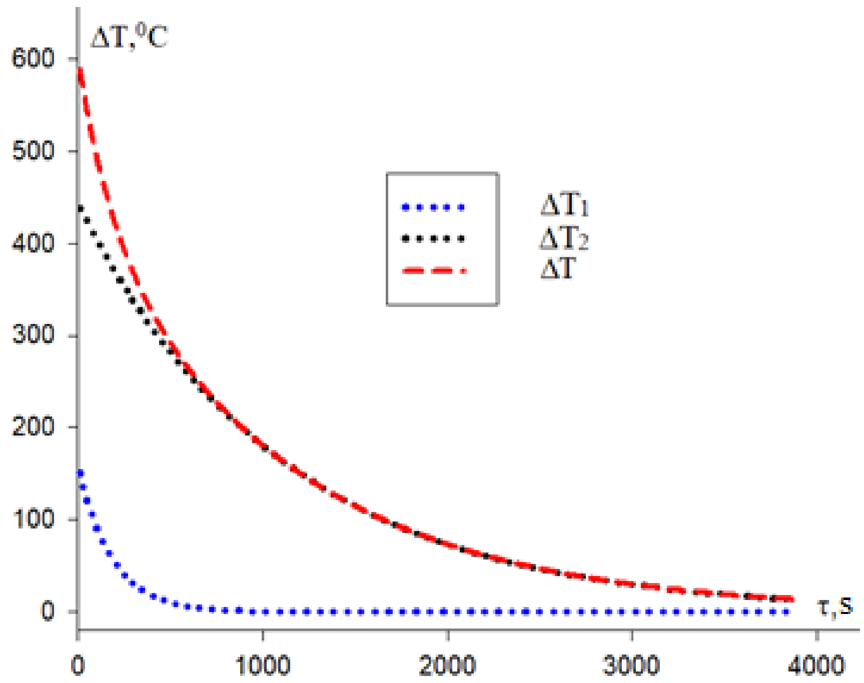

Figure 4 The dependence of the sample temperature on the cooling time for A5N aluminum with a diameter of 3.5 cm.

As can be seen from the **Figures 3** and **4**, cooling due to thermal radiation proceeds faster than with convective heat transfer. The contribution of thermal radiation to heat transfer is noticeable at high temperatures.

As an example, **Figure 5** shows the dependence of the cooling rate on time for a sample of A5N aluminum with a diameter of 4.0 cm.

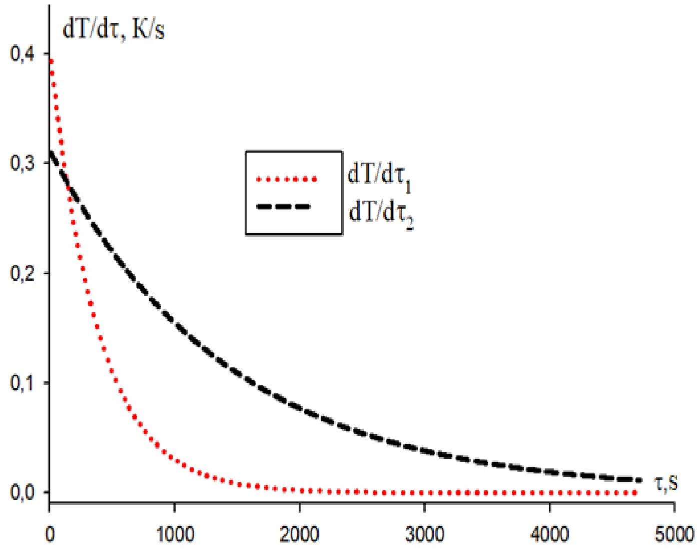

Figure 5 Dependence of the cooling rate on time for a sample of A5N aluminum with a diameter of 4.0 cm.

Determination of the constant value of thermophysical properties is one of the most important works in such studies, since these constants are necessary parameters in the development of devices and the design of materials with the required properties. In table, **Figure 1** shows the found values of the constants included in the equation for the dependence of the temperature of the studied samples of A5N aluminum on time (Eq. (3)).

Table 1 Value of constants in Eq. (3).Variation of the temperature of the alloy A5N depending on the diameter of the samples.

Diameter, m	T_1-T_0, K	τ_1, s	T_2-T_0, K	τ_2, s
0.015	175.5	48.31	425.3	454.54
0.02	175.0	51.81	425.1	640.00
0.025	174.8	76.19	426.9	820.28
0.03	160.5	116.09	439.7	960.1
0.035	159.1	180.92	442.41	1111.1
0.04	155.4	384.61	445.5	1428.6

According to the results given in **Table 1** (check the decimals, please put "." Not a ","), it should be noted that for the same cylindrical aluminum sample, with an increase in its diameter, the difference in the value of T_1-T_0 decreases, and τ_1 increases back to this. However, T_2-T_0 is characterized by a different pattern of changes. The difference in T_2-T_0 first slightly decreases and then sharply increases, but despite this, τ_2 always increases.

Figure 6 show the dependence of the characteristic cooling time due to thermal radiation and convective heat transfer on the ratio of the sample volume to its surface area V/S for A5N grade aluminum.

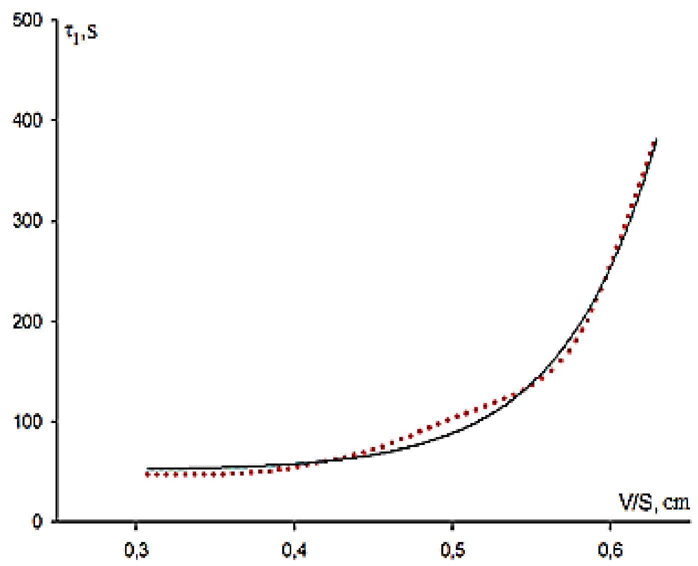

Figure 6 Dependence of the characteristic time of cooling due to irradiation on V/S for samples made of A5N aluminum.

Processing of the curved dependence of the characteristic cooling time due to irradiation on V/S for aluminum samples of different grades using the Sigma Plot 10 program showed that it is expressed by the equation:

$$\tau_1 = \tau_0 + ae^{bx} ,$$

where $x=V/S, \tau_0=51.27s; a=0.0084\ s; b=16.83\ s/cm$. Regression coefficient R = 0.998.

Similar to the results above, **Table 2** shows the cooling rates versus time found from Eq. (4) for A5N aluminum samples.

Table 2 Value of constants in Eq. (4): Behavior of the cooling rate A5N depending on the diameter of the samples.

D, m	$\frac{T_1-T_0}{\tau_1}, \frac{K}{s}$	$\frac{T_2-T_0}{\tau_2}, \frac{K}{s}$	**T_0, K**
0.015	3.63	0.93	300.1
0.02	3.37	0.66	302.0
0.025	2.29	0.52	304.8
0.03	1.38	0.46	301.9
0.035	0.88	0.39	302.1
0.04	0.40	0.31	309.6

Figure 7 show the dependence of the characteristic cooling time due to thermal radiation and convective heat transfer on the ratio of the sample volume to its surface area V/S for A5N grade aluminum.

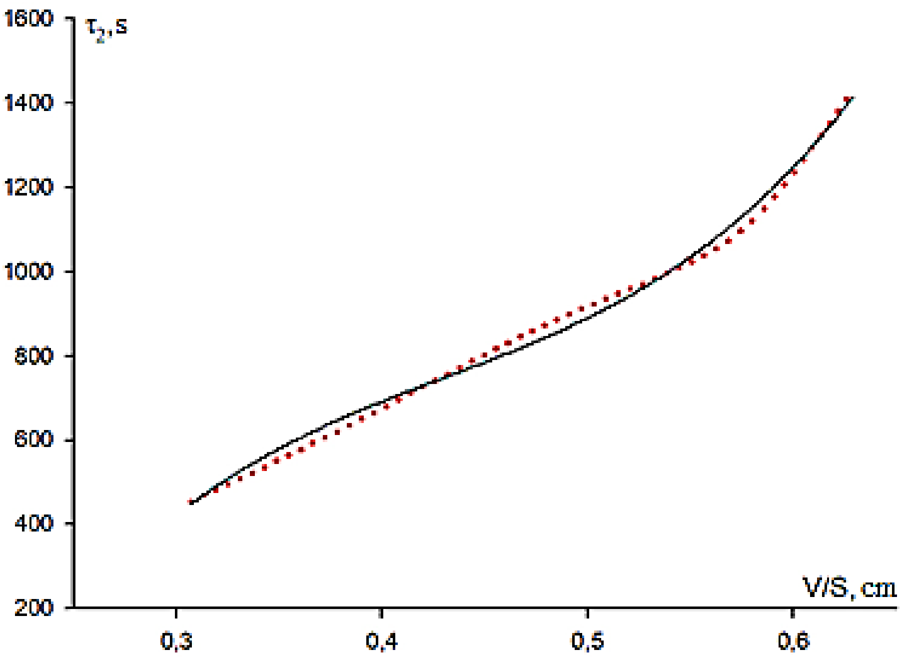

Figure 7 Dependence of the characteristic cooling time due to convective heat transfer on V/S for A5N aluminum specimens.

Processing the obtained results on the dependence of the characteristic cooling time due to convective heat transfer on V/S for samples made of A5N grade aluminum showed that it obeys a cubic equation of the type (x = V/S, cm):

$$\tau_2 = \tau_0 + ax + bx^2 + cx^3,$$

where: $\tau_0 = -3128.7$ s; $a = 23313.2 \frac{s}{cm}$, $b = -49820.7 \frac{s}{cm^2}$, $c = 38540.1 \frac{s}{cm^3}$.

We also determined the nature of the change in the values of $\frac{T_1 - T_0}{\tau_1}$ and $\frac{T_2 - T_0}{\tau_2}$ for the constant cooling of the first and second heat transfer processes, depending on the diameter of the samples under study. The results of the dimensional (diametric) dependences of the $\frac{T_1 - T_0}{\tau_1}$ and $\frac{T_2 - T_0}{\tau_2}$ are shown in **Figure 8**.

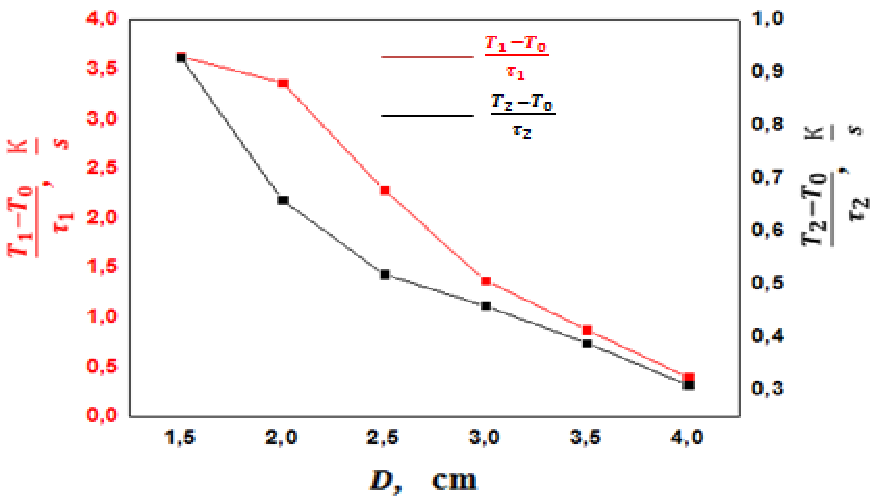

Figure 7 Dependences of the constant values of $\frac{T_1 - T_0}{\tau_1}$ and $\frac{T_2 - T_0}{\tau_2}$ on the diameter of the studied samples.

From **Figures 1** and **2** shows that the temperature of the A5N sample heated to 900 K decreases exponentially with time, the reason for which is convective heat exchange from the environment and thermal radiation. On the other hand, it was noticeable that the temperature of the smaller diameter samples dropped faster than the larger diameter samples. This was also confirmed by the results of measuring the dependence of the cooling rate on time. At the same time, the patterns of temperature change in samples of smaller diameter somewhat deviate from the standard picture of temperature change. According to the results obtained, the cooling time of the samples due to thermal radiation, shown in **Figure 6**, increases exponentially with increasing V/S ratio. In the case of convective cooling, the exponentiality is violated.

Thus, the results obtained in the work can serve as a basis for further study of the thermophysical and thermodynamic properties of A5N and other grades of aluminum alloys of various shapes and sizes [48-56].

Conclusions

The effect of the size of cylindrical samples of A5N aluminum on the time and rate of spontaneous air cooling has been studied. It is assumed that the samples are cooled due to convective heat transfer and thermal radiation. The characteristic cooling time due to radiation is less than the characteristic cooling time due to convection. The effect of thermal radiation on the cooling process is noticeable at high temperatures. It has been established that the characteristic times of cooling due to thermal radiation and convective heat transfer increase nonlinearly with an increase in the volume-to-area ratio of the sample. Using experimentally found values of the cooling rate, mass and area of samples, temperature environment, the ratio of the heat transfer coefficient to the specific heat capacity of the samples was calculated. The error in determining the cooling rate at high temperatures is less than for temperatures close to the rooms. The regularities found confirm the results obtained by us for samples made of aluminum grades A6 and A0.

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