============================ **CHEMICAL THERMODYNAMICS**
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Studying the Viscosity of Liquid Aluminum−Nickel Alloys

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Abstract—Temperature and concentration dependences of the viscosity of melts of the Al−Ni system are obtained experimentally in a wide range of temperatures (from liquidus to 1700°C) and concentrations (nickel content, 0 to 100 at %). The temperature dependences of the viscosity obtained in the heating and cooling modes coincide, and there is no hysteresis. Viscosity isotherms have a nonmonotonic form with maximum values at nickel contents of 50−65 at % and a minimum at 85 at %. The nonmonotonic viscosity isotherms of liquid alloys are explained by a change in the type of short-range ordering in a melt upon a change in concentration.

INTRODUCTION

With relatively low weight, alloys of the Al−Ni system have high corrosion resistance and unique mechanical properties that are retained at elevated temperatures. This binary system is the basis of a whole class of materials called superalloys, which are used in manufacturing products that operate under extreme conditions, turbine engine blades in particular. Alloys with an amorphous and quasicrystalline structure have been obtained on the basis of the Al−Ni system. To develop materials with desired properties, information is needed on the structural features and physicochemical properties of basic systems in both the solid and liquid states. The liquid phase plays a key role, since most metallic materials are obtained with its direct participation. This is especially important when it comes to materials obtained directly from the liquid state, e.g., cast alloys obtained by ultrafast cooling of the melt (amorphous alloys), or by means of directed crystallization.

Indirect means of research based on measuring the temperature, concentration, and temporal dependences of such structure-sensitive properties of a liquid as viscosity are often used when studying the structural features of melts and analyzing interparticle interaction [1]. The availability of reliable experimental data on the viscosity of melts is also important for developing the theory and models of the liquid state [2−4], in addition to most metallurgical processes associated with passing through the liquid phase.

The viscosity of Al−Ni melts has been studied in detail in the region rich in aluminum with nickel contents up to 10% (here and below, the content of nickel in an alloy is indicated in at %) [5−9]. A comparative analysis of these data was performed in [9]. Three works [10−12] have been devoted to experimental studies of the viscosity of aluminum−nickel melts in a wide range of concentrations. However, the data obtained by the authors of these works are very contradictory. The authors of [10, 11] noted a sharp maximum in the concentration dependence (isotherm) of viscosity near the equiatomic composition, but their data on the absolute values of viscosity differ greatly. In [11], a minimum was fixed on the viscosity isotherm corresponding to the Ni_3Al intermetallic compound, which missing according to the data in [10]. A sharp maximum on the viscosity isotherm was not observed in [12]. In our opinion, one of the main reasons for such a considerable difference in the experimental data is the results from measuring surface effects associated with the formation of a viscous film at the free boundary of the melt and/or the formation of a meniscus [13].

Temperature dependences (polytherms) of the viscosity of Al−Ni melts with nickel contents of more than 10% were presented in [11, 12]. In [12], however, polytherms were obtained only in the cooling mode, and the modes of recording polytherms were not indicated in [11]. For a more complete analysis of features

of the structural state of melts, we must study the temperature dependences of their properties in the heating and subsequent cooling modes.

In this work, we studied the temperature dependence of viscosity (here and below, unless otherwise indicated, viscosity is understood as kinematic viscosity) in the heating and cooling modes, and the concentration dependence of the viscosity of melts of the Al–Ni system in a wide range of concentrations (nickel content, 0 to 100%) using a procedure that excludes the influence of film effects.

EXPERIMENTAL

Our objects of study were pure aluminum, nickel, and Al–Ni binary alloys with nickel contents of 10, 25, 35, 50, 65, 75, and 85%. Samples were obtained by alloying master alloy $Al_{75}Ni_{25}$ with aluminum or nickel in a viscometer furnace. The master alloy was obtained by melting metals in a resistance furnace for 30 min at a residual pressure of 10^{-2} Pa and a temperature of 1670°C. The initial components were high-purity aluminum (99.999 wt % Al) and electrolytic nickel (99.95 wt % Ni). The content of nickel in the alloys was determined via atomic emission spectroscopy on a SPECTRO Flame Modula D spectrometer.

The kinematic viscosity of the melts was measured according to torsional vibration [14] on an automated setup [15]. Measurements were made in a protective helium atmosphere. Crucibles with lids floating on the melt were used to eliminate the influence of film effects and wetting phenomena on measuring results. Cylindrical Al_2O_3 cups 40 mm tall and with an inner diameter of 17 mm were used as crucibles. The lids were made from Al_2O_3 cups 12 mm tall and with outer diameters 0.4–0.6 mm smaller than the inner diameters of the crucibles. The design of a crucible with a lid is shown in [16]. The lids moved along the vertical axis of the crucible to compensate for changes in sample volume. When performing torsional vibrations, the lids moved along with the crucibles, creating an additional end face of friction with the melt.

When studying the concentration dependence of the properties of the Al–Ni system in the region rich in aluminum, the need arises for high overheating of the melts with respect to their liquidus temperatures, due to the considerable difference between them (from 660°C for pure aluminum to 1638°C for the $Al_{50}Ni_{50}$ alloy [17]). Reliable viscosity data were obtained for pure aluminum when it was heated to 1400°C. When heated more, the liquid metal rose in the gap between the walls of the crucible and the lid, which negatively affected the measuring results. The viscosity of $Al_{90}Ni_{10}$ liquid alloy was measured in the heating mode up to 1200°C and subsequent cooling and in the cooling mode from 1700°C. For other alloys, the temperature dependence was measured in the heating and cooling modes in the liquidus to 1700°C range of temperatures, with isothermal holding at each temperature for 15 min. Before measurements, the binary alloys were remelted at a temperature of 1670°C for 30 min and allowed to cool until the melt solidified. The alloy was then heated to the melting temperature and measurements began.

The liquidus temperatures of the alloys in our viscometric experiment were determined from the temperature dependence of the damping decrement of free torsional vibrations of a crucible with a sample. The melting of the alloys was accompanied by a sharp rise in the damping decrements, due to increased proportions of the liquid phase. The sharp rise in the decrements was replaced by a gradual decline in the heating mode at the liquidus temperature in the weakly viscous approximation [14] used in our experiment.

When calculating viscosity by numerical means, we solved the equation [14, 15]

$$f(\nu) = \text{Re}(L) + \frac{\delta}{2\pi}\text{Im}(L) - 2I\left(\frac{\delta}{\tau} - \frac{\delta_0}{\tau_0}\right), \qquad (1)$$

where δ, τ, δ_0, τ_0 are the damping decrements and periods of oscillation of the suspension system with and without melts, respectively; I is the moment of inertia of the suspension system; and $\text{Re}(L)$ and $\text{Im}(L)$ are the real and imaginary parts of friction function

$$L = -2\nu m\beta \frac{J_2(\beta)}{J_1(\beta)} + 4n\pi\rho R^2 \frac{k^2}{\nu}\sum_{n=1}^{\infty}\frac{\text{th}\left(\frac{\vartheta_n H}{2}\right)}{\mu_n^2 \vartheta_n^3}. \qquad (2)$$

In expression (2), ν is the kinematic viscosity of the melt; m, R are the mass and radius of the sample; $H = \dfrac{m}{\pi R^2 \rho}$ is the height of the liquid in the cup; ρ is the density of the liquid; J_1 and J_2 are Bessel functions of the first kind of the first and second order, respectively; $\beta = R\sqrt{(\delta + 2\pi i)/\tau\nu}$, μ_n are the characteristic numbers determined from the equation $J_1(\mu_n R) = 0$; $\vartheta_n = \sqrt{\mu_n^2 - (\beta/R)^2}$; $k = \dfrac{\delta}{\tau} + \dfrac{2\pi i}{\tau}$; $i = \sqrt{-1}$; and $n = 2$ is the number of end friction faces of the sample and the crucible. The thermal expansion of the crucible material was considered when determining the radius. (In the range of 20–1800°C, the linear coefficient of thermal expansion of Al_2O_3 was 9.0×10^{-6} deg^{-1} [18].) The densities of melts were determined from the experimental data [19, 20] using approximations of the temperature dependence of density according to a linear equation and the concentration dependence according to a second-order polynomial (reliability R^2 of approximation was at least 0.993).

The total relative error in determining viscosity [15, 21] was no more than 4%. The error of a single experiment was no more than 2%.
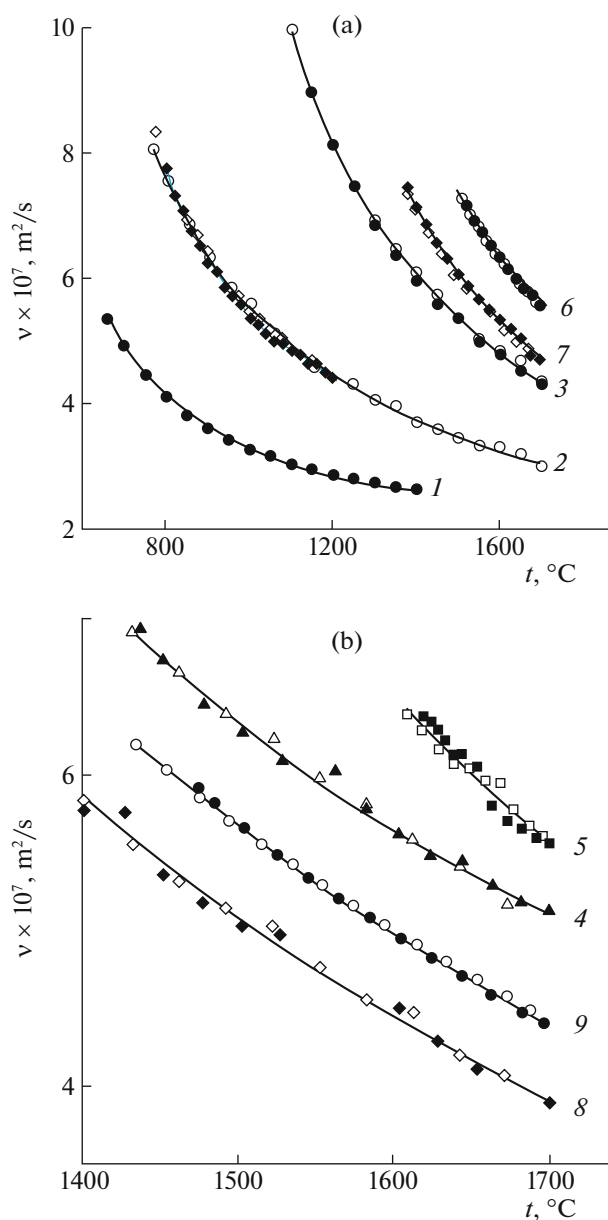
Fig. 1. Temperature dependences of the kinematic viscosity of Al−Ni melts (black points were obtained in the heating mode; white points, in the cooling mode): (*1*) pure Al, (*2*) $Al_{90}Ni_{10}$ melt, (*3*) $Al_{75}Ni_{25}$, (*4*) $Al_{65}Ni_{35}$, (*5*) $Al_{50}Ni_{50}$, (*6*) $Al_{35}Ni_{65}$, (*7*) $Al_{25}Ni_{75}$, (*8*) $Al_{15}Ni_{85}$, and (*9*) pure Ni. In this figure, the solid lines on the graphs are the spline approximations of the experimental points.

RESULTS AND DISCUSSION

The temperature dependences of the kinematic viscosity of Al−Ni melts are presented in Fig. 1. The values of melt viscosity for all of the alloys fall monotonically as the temperature rises. The polytherms obtained in the heating and cooling modes coincide within the experimental error (i.e., there is no hysteresis in the viscosity polytherms).
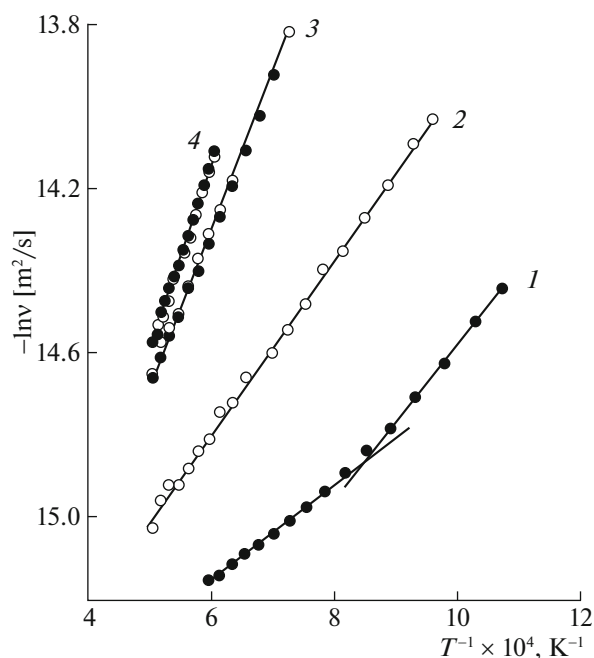

Fig. 2. Dependences of the logarithm of viscosity on the reciprocal absolute temperatures of (*1*) liquid aluminum and (*2*) $Al_{90}Ni_{10}$, (*3*) $Al_{75}Ni_{25}$, (*4*) $Al_{25}Ni_{75}$ melts.

The temperature dependences of viscosity were approximated using the Arrhenius equation [14]

$$\nu = A \exp\left(\frac{E_\nu}{RT}\right), \tag{3}$$

where A is a constant, R is the universal gas constant, T is the absolute temperature, E_ν is the energy of activation of the viscous flow. Typical dependences of the logarithm of viscosity on the reciprocal temperature are shown in Fig. 2. Except for pure aluminum, the viscosity polytherms of the melts are described well by the Arrhenius equation, as is confirmed by the linear dependence of the viscosity logarithm on the reciprocal absolute temperature (Fig. 2, curves *2*−*4*).

With liquid pure aluminum (Fig. 2, curve *1*), a break is observed in the $\ln \nu = f(1/T)$ dependence in the 900−930°C range of temperatures, indicating a sharp change in the energy of activation of the viscous flow. The break in the viscosity polytherm of liquid aluminum near 910°C was discussed in [9, 22, 23], and was presumably due to structural transformation in liquid aluminum.

The viscosities given in Table 1 for the melts at fixed temperatures were determined according to the polytherms. The concentration dependences of viscosity at a fixed temperature (isotherms) are non-monotonic (Fig. 3, curve *1*). In the concentration range from 0 to 85% Ni, they have a domed shape with maximum viscosities at a nickel content of 50−65%. It should be noted that even at a relatively low nickel

Table 1. Values of kinematic viscosity of melts ($v \times 10^7$ m^2/s) at fixed temperatures

x(Ni), at %	900°C	1100°C	1300°C	1400°C	1500°C	1600°C	1700°C
0	3.44	3.10	2.88	2.79	2.71*	2.65*	2.59*
10	6.42	4.73	3.75	3.45	3.26	3.13	3.05
25	—	9.97	6.90	6.03	5.37	4.83	4.37
35	–	—	—	—	6.37	5.68	5.05
50	–	—	—	—	—	6.48*	5.52
65	–	—	—	—	7.41	6.32	5.53
75	–	—	—	7.10	6.03	5.30	4.63
85	–	—	—	—	5.06	4.43	3.89
100	–	—	—	—	5.68	4.99	4.40

* Determined by approximating the viscosity polytherm according to Arrhenius equation (3) with subsequent interpolation of the equation to a given temperature.

content (10%), alloying aluminum with nickel leads to a sharp increase in melt viscosity, which is especially pronounced with decreasing temperature (Table 1). In the region of nickel-rich alloys, the isotherm shows a viscosity minimum corresponding to the Al$_{85}$Ni$_{15}$ melt. When the temperature of the melt changes, the character of the viscosity isotherm is preserved.

To compare the data obtained in this work with the literature data, Fig. 3 additionally shows the concentration dependences of the kinematic viscosity of Al−Ni melts at a temperature of 1700°C according to the data of [10−12]. The values of viscosity on curves 2 and 3 (Fig. 3) are determined, respectively, from the graphs of concentration [10] and temperature dependences [11] of kinematic viscosity. The values on curve 4 were calculated using the dynamic viscosity
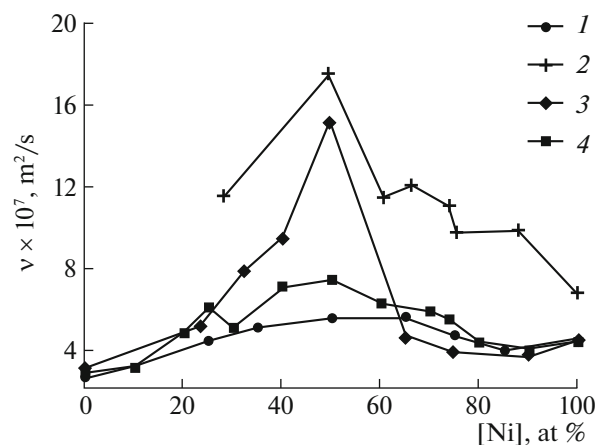
and density polytherm equations presented in [12]. Figure 3 shows that the results of our studies on the nature of the concentration dependence of viscosity are in good agreement with the data of [12]. The sharp maximum of viscosity near the equiatomic composition, previously observed by the authors of [10, 11], is not confirmed. In the concentration ranges rich in aluminum or nickel (the content of the second element is up to 25%), the data obtained in this work are in good agreement with the data of works [11, 12], especially [12], in terms of the absolute values of viscosity. In the concentration range with the content of both components more than 30% (near the equiatomic composition), the viscosities obtained by us turn out to be lower than the values from [12]. This could be due to Kehr et al. [12] using the densities calculated in [24], which differ notably from the experimental data known in [19, 20], when calculating the viscosity. The viscosities obtained in [10] are considerably overestimated, relative to the data from other authors for both liquid binary alloys and pure nickel, and are most likely erroneous.

The discrepancy between the experimental data on the viscosity of melts, especially pure metals, obtained by different authors, is usually explained by differences in the purity of the studied materials, the use of different research methods and experimental conditions. As applied to the Al−Ni system, all known experimental data [10−12] were obtained from damped torsional vibrations in the Shvidkovsky [10, 11] and Roscoe [12] variants on samples melted using high-purity metals.

Fig. 3. Concentration dependences of the kinematic viscosity of Al−Ni melts at 1700°C: (1) results in this work; data of the authors of (2) [10], (3) [11], and (4) [12].

In Shvidkovsky's variant [14], the kinematic viscosity of the melt in the weakly viscous approximation ($y = 2\pi R^2/\tau\nu \geq 100$) is calculated using the formula

$$\nu = \frac{1}{\pi}\left(\frac{I}{mR}\right)^2 \frac{(\delta - (\delta_0/\tau_0)\tau)^2}{\tau\sigma^2}, \qquad (4)$$

where $\sigma = 1 - \frac{3}{2}x - \frac{3}{8}x^2 - a + \left(\frac{2nR}{H}\right)(b - cx)$, $a = 3/\sqrt{2y}$, $x = \delta/2\pi$, b and c are coefficients that depend on parameter y [14].

According to Roscoe in [25], the dynamic viscosity of the melt is calculated as

$$\eta = \left(\frac{I\delta}{\pi R^3 HZ}\right)^2 \frac{1}{\pi\rho\tau}, \qquad (5)$$

where η is the dynamic viscosity of the melt, $\eta = \nu\rho$;

$$Z = \left(1 + \frac{nR}{4H}\right)a_0 - \left(\frac{3}{2} + \frac{4nR}{\pi H}\right)\frac{1}{p}$$
$$+ \left(\frac{3}{8} + \frac{9nR}{4H}\right)\frac{a_2}{2p^2} - \left(\frac{63}{128} - \frac{45nR}{64H}\right)\frac{a_4}{4p^4} + \Lambda,$$

$$a_0 = (1 - \Delta)\sqrt{\frac{\sqrt{1 + \Delta^2} + 1}{2}} - (1 + \Delta)\sqrt{\frac{\sqrt{1 + \Delta^2} - 1}{2}},$$

$$a_2 = \sqrt{\frac{\sqrt{1 + \Delta^2} + 1}{2}} - \sqrt{\frac{\sqrt{1 + \Delta^2} - 1}{2}},$$

$$a_4 = \frac{a_2}{\sqrt{1 + \Delta^2}}, \qquad p = R\sqrt{\frac{\pi\rho}{\eta\tau}}, \qquad \Delta = \frac{\delta}{2\pi}.$$

The denotation of quantities in formulas (4) and (5) coincides with those in expressions (1) and (2).

To compare means of calculation, the viscosity of the melts was calculated using formulas (1), (4), and (5). The calculated results for one experimental point ($Al_{75}Ni_{25}$ melts at a temperature of 1702°C) are given in Table 2. Using different equations to calculate viscosity, especially the numerical solution to Eq. (1), the Shvidkovsky equation for low-viscosity liquids (4) (used by the authors of [10, 11]), and Roscoe's Eq. (5), does not appreciably affect the final results, provided that the damping decrement of an empty suspension system (used in [12]) is considered. The relative deviations of the viscosities obtained using the Shvidkovsky and Roscoe equations with respect to the viscosities found by numerically solving Eq. (1) ($\Delta\nu/\nu$) are 0.8 and 0.7%, respectively (Table 2). As expected, using the Roscoe formula without allowing for the zero damping decrement results in overestimated viscosities.

In our opinion, the main reasons for the considerable scatter in the data of different authors presented in Fig. 3 are film effects and wetting phenomena, the strong influence of which on the results from measuring viscosity was shown earlier using the example of pure Al [26] and alloys based on Co [27] and Fe [28]. Film effects are associated with the formation of viscous oxide films at the free boundaries of melts. These films result in overestimates of the damping decrements of the torsional vibrations of crucibles with melts measured in experiments, and thus the calculated viscosities. The influence of wetting phenomena is expressed in the formation of a meniscus at the boundary of a melt and the side walls of a crucible as a result of strong or weak wetting of the crucible by the melt. The formation of a concave meniscus results in an overestimated effective height of a melt (an increased area of contact between the melt and the side wall of the crucible), which is reflected by an increase in the damping decrement and melt viscosity. In contrast, the formation of a convex meniscus is accompanied by underestimated values of viscosity obtained in an experiment.

The studies performed in this work differ fundamentally from those presented in [10–12], since we used a crucible with a floating lid to measure viscosity. The presence of a floating lid on the upper boundary of a melt eliminates the influence of film effects and wetting phenomena, since the test sample is in contact with the crucible from all sides and has a cylindrical shape. Careful study of the research methodology and the setting up of the experiment allow us to obtain reliable data on the viscosity of liquid alloys.

In studying the concentration dependence of viscosity, we performed a physicochemical analysis of liquid systems and solutions that consisted of comparing isotherms of their properties and an isotherm of an "ideal" system constructed by assuming there was no chemical interaction between atoms of different types [29]. The viscosity isotherm of such an ideal system can
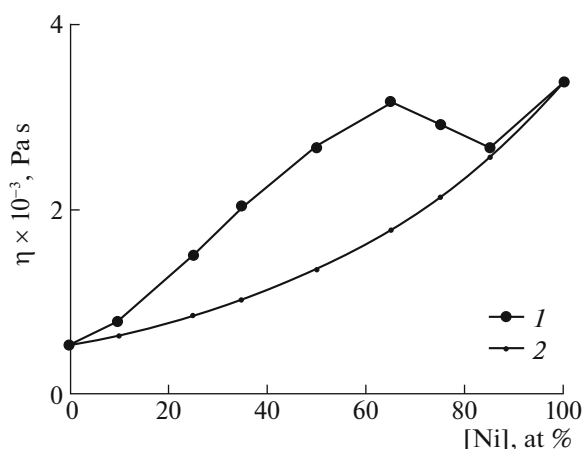
Table 2. Results from calculating the viscosity of an $Al_{75}Ni_{25}$ melt using different formulas

Formula	$\nu \times 10^{-7}$, m^2/s	$\frac{\Delta\nu}{\nu}$, %
Numerical solution to Eq. (1)	4.368	—
Shvidkovsky's formula (4)	4.403	0.80
Roscoe's formula (5) with no allowance for δ_0 $\delta^* = (\delta - \delta_0)$	4.397	0.66
Roscoe's formula with no allowance for δ_0	5.287	21.04

Parameters used in our calculations were $t = 1702$°C, $\delta = 0.08257$, $\tau = 4.229$ s, $I = 3.1451 \times 10^{-6}$ kg m^2, $R = 8.527 \times 10^{-3}$ m, $m = 11.36 \times 10^{-3}$ kg, $\delta_0 = 0.0055$, $\tau_0 = 4.1528$ s, and $\rho = 3456$ kg/m^3.

$\frac{\Delta\nu}{\nu}$ is the relative deviation.

Fig. 4. Concentration dependence of dynamic viscosity of Al−Ni melts at 1700°C: (*1*) results of this work, (*2*) additive dependence calculated with formula (6).

Fig. 5. Concentration dependence of the absolute deviation of the dynamic viscosity of a melt (Δη) on the viscosity isotherm of an ideal system (the additive dependence of the logarithm of viscosity).

be determined from the additivity condition for the logarithm of the viscosity according to the formula [29]

$$\ln \eta_{\text{id}} = x_1 \ln \eta_1 + x_2 \ln \eta_2, \qquad (6)$$

where η_{id} is the dynamic viscosity of the ideal system, η_1 and η_2 are the dynamic viscosities of the mixture's components (pure aluminum and nickel), and x_1 and x_2 are their mole fractions.

Figure 4 shows the concentration dependence of the dynamic viscosity at a temperature of 1700°C, calculated from the kinematic viscosity isotherm obtained in this work using the experimental data on density [19, 20] and the isotherm of an ideal system calculated according to formula (6). Figure 4 shows that in the range of concentrations up to 80% Ni, there is considerable positive deviation of the viscosity isotherm obtained experimentally from that of an ideal system. The concentration dependence of the difference between these isotherms is shown in Fig. 5. In the range of concentrations rich in aluminum, a substantial increase in viscosity (compared to an ideal system) is observed at a relatively low content of nickel, which is consistent with results from studying the concentration dependence of the viscosity of Al−Ni melts with low contents of nickel [7−9]. The deviation of the viscosity isotherm obtained in the experiment from the isotherm of an ideal system is maximal at nickel contents of 50−65%. In the region rich in nickel, the dynamic viscosity is close to that of an ideal system at the corresponding concentrations of nickel, especially for the liquid $Al_{15}Ni_{85}$ alloy.

A strong positive deviation of the viscosity isotherm from the additive dependence is typical of systems with strong chemical interaction between the melt components. This is additional confirmation of chemical short-range order in the melt. We would expect the maximum deviation of the experimental viscosity is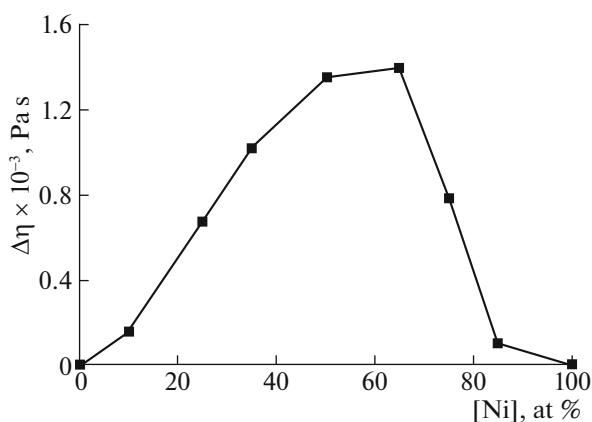otherm from that of an ideal system to cor-respond to the melt with the highest degree of ordering. Chemical short-range order in melts of the Al−Ni system has been noted in a number of works (e.g., [30−33]). The average order is preserved in liquid Al−Ni alloys [31−33], due to the formation of atomic clusters from aluminum and nickel atoms ordered according to the type of intermetallic compounds. The presence of aluminum−nickel clusters in the melt is confirmed by the first peak on the diffraction curves in the region of small scattering angles [32, 33].

The nonmonotonic viscosity isotherms of liquid alloys of the Al−Ni system can thus be explained by a change in the type of short-range ordering in the melt upon a change in composition. At contents of nickel in a melt up to 80%, there are apparently atomic microgroups (clusters) with chemical short-range ordering close to that of intermetallic compounds. The highest degree of ordering is characteristic of melts with nickel contents of 50−65%, which corresponds to the maximum deviation of the viscosity isotherm of a real melt from an ideal one. Considering the proximity of this maximum to the stoichiometric composition of the AlNi compound, we may assume short-range ordering of the type of the AlNi compound occurs in the melt in this range of concentrations. The shift of the maximum toward higher nickel contents can be explained by the wide range of the homogeneity of the AlNi compound's concentration [17]. In addition to clusters of the AlNi type, others with high contents of nickel (e.g., of the Al_3Ni_5 type) can be present in a melt. The latter assumption is based on results from the thermodynamic modeling of the Al−Ni system performed in [34], according to which the melt in the considered range of concentrations contains such associates as AlNi and Al_3Ni_5, the total volume fraction of which is maximal at a nickel content of 60%.

In the region rich in aluminum, clusters of the type of intermetallic compounds (presumably Al$_3$Ni) form even at relatively low contents of nickel, as indicated by the considerable increase in viscosity upon raising the concentration of Ni, compared to the isotherm of an ideal melt (Fig. 4). This agrees with the results from studying the structure [35] and viscosity isotherms [8] of Al−Ni melts with a low contents of nickel. In melts rich in nickel (with contents of more than 80%), the short-range ordering of atoms apparently proceeds according to the type of a solid solution of aluminum in nickel (with a random arrangement of aluminum atoms), as is indicated by the similarity between the viscosities of the liquid Al$_{15}$Ni$_{85}$ alloy and the viscosity of an ideal system at a corresponding concentration of nickel (Fig. 4). This assumption corresponds to the relatively high limiting solubility of aluminum in solid nickel (22.2% at 1385°C [17]).

CONCLUSIONS

We studied the temperature dependences of the kinematic viscosity of liquid Al−Ni alloys in a wide range of concentrations (content of nickel, 0 to 100%) upon heating from liquidus to 1700°C with subsequent cooling. The temperature dependences of viscosity were monotonic for all of the considered melts. Polytherms obtained in the heating and cooling modes coincided.

The concentration dependences of the kinematic viscosity of Al−Ni melts were nonmonotonic, with maximum values of viscosity at nickel contents of 50−65% and a local minimum at 85% Ni. The sharp maximum of the viscosity isotherm observed by the authors of [10, 11] near the equiatomic composition was not confirmed.

There was considerable deviation of the isotherm of the dynamic viscosity of melts of the Al−Ni system from that of an ideal melt, calculated according to the additivity of the logarithm of viscosity. The greatest deviation was observed at 50−65% Ni. The viscosities were close to an additive dependence in the region rich in nickel (content of nickel, greater than 85%).

Nonmonotonic viscosity isotherms of liquid alloys of the Al−Ni system are explained by a change in the type of short-range ordering in a melt upon a change in concentration. At contents of nickel up to 80%, atomic microgroups (clusters) with chemical short-range ordering close to that of intermetallic compounds form in the melt, which has the highest degree of ordering in the 50−65% range of concentrations. In nickel-rich melts (content of nickel, greater than 80%), the short-range ordering of atoms proceeds according to the type of the solid solution of aluminum in nickel.

CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

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