Journal of Non-Crystalline Solids 410 (2015) 1–6

Contents lists available at ScienceDirect

Journal of Non-Crystalline Solids

journal homepage: www.elsevier.com/locate/jnoncrysol

The viscosity of binary Al–Fe melts in the Al-rich area

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ARTICLE INFO

Article history:
Received 18 July 2014
Received in revised form 3 November 2014
Accepted 30 November 2014
Available online 12 December 2014

Keywords:
Melt;
Viscosity;
Hysteresis;
Macrostructure

ABSTRACT

The temperature and concentration dependencies of the kinematic viscosity of liquid binary alloys of Al–Fe (up to 6.5 at.% Fe) have been studied. For the melts with an iron content less than 1.5% the deviation of the viscosity polytherms from the Arrhenius dependence polytherms has been found presumably due to the structural transformation in liquid aluminum. Hysteresis of the temperature dependences of viscosity of the melts with an iron content of 3 to 6.5% obtained during heating and subsequent cooling has been found. Hysteresis of the viscosity polytherms is the result of irreversible destruction of nonequilibrium atomic microgroups, supposedly, Al_5Fe_2-type clusters, which are formed by the melting of the Al_3Fe crystals.

1. Introduction

Aluminum alloys doped with metals of the iron group (Fe, Ni, Co) are the basis of easily amorphizing compositions, Al-(Fe/Ni/Co)-REM, which have high strength properties in comparison with cast industrial alloys while maintaining ductility and corrosion resistance [1,2]. In the study of liquid aluminum-based alloys, including amorphizing ones, long non-monotonic relaxation processes [3] and structural changes in them at certain temperature have been found [4,5]. These phenomena may be due to inheritance upon melting elements of short-range ordering characteristic of the initial multiphase samples [6]. To clarify their nature it is important to study the structure and properties of simple model binary systems.

Additional interest in the binary Al-(Fe/Ni/Co) systems in the Al-rich area is due to the formation of eutectics in them at a relatively low content of the alloying element [7]. Meanwhile, the question of the melt structure in systems with the eutectic phase diagram remains controversial and topical. In the study of the features of their structures indirect methods based on the measurement of various structural-sensitive properties, particularly, viscosity, are frequently used.

Temperature and concentration dependence of the viscosity of liquid aluminum-rich binary Al–Ni and Al–Co alloys are studied in detail in [8]. In doing so, the deviation of the temperature dependences of the viscosity from the Arrhenius dependences for the melts with the content of 2.7–5 at.% Ni and less than 1.5 at.% Co was found. In addition, a non-monotonic concentration dependence of the viscosity of the Al–Ni system melts was detected [8].

Published data on the viscosity of melts in the Al–Fe system in the area rich in aluminum are few and contradictory [9–14]. The temperature and concentration dependences of the viscosity of the melts containing less than 2.5 at.% Fe when heated to 950 °C were obtained in [9–11]. In [12] the temperature dependences of the viscosity of the melts containing up to 1.5 at.% Fe in the range from the liquidus temperature to 1100 °C were measured. The temperature dependences of the viscosity of liquid alloys for some hypereutectic compositions (from 1.5 to 4 at.% Fe) were studied by the authors in [13,14].

According to [9,10] the temperature dependences of the viscosity of the Al–Fe melts with the content of Fe less than 2.5 at.% are monotonic and are described by the Arrhenius equation. It is shown that an increase in the iron content leads to an increase in the viscosity values [9–11]. However, in [12] sharp changes were found in the viscosity of the liquid alloys containing up to 1.5 at.% Fe on heating near 950 °C which, according to the authors, are due to the structural transformation in liquid aluminum. Features in the form of continuous growth of the values with increasing the temperature near the liquidus [14] and hysteresis of the polytherms obtained during heating and subsequent cooling [11,13,14] were found on the temperature dependences of the viscosity of the melts of hypereutectic compositions.

In this regard, temperature (polytherms) and concentration (isotherm) dependences of the kinematic viscosity of the binary Al–Fe melts with an iron content up to 6.5 at.% are investigated in this paper.

2. Objects and experimental procedure

The samples under study were prepared by alloying A999-type Al and alloy, $Al_{90}Fe_{10}$, in a viscosimeter furnace under high pure helium conditions at 1100 °C for no less than 1 h. The $Al_{90}Fe_{10}$ alloy was obtained by alloying the metals in a resistance furnace at the residual pressure,

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http://dx.doi.org/10.1016/j.jnoncrysol.2014.11.028

10^{-2} Pa, at 1670 °C for 30 min. The initial components were the elements with the content of the basic metal: aluminum 99.999 and iron 99.98 mass%.

Kinematic viscosity of the melts (ν) was measured using the automated equipment [15] by the damped torsional vibration method [16]. All the measurements were carried out in the atmosphere of high purity helium. Cylindrical Al_2O_3 crucibles with an inner diameter of 16 mm and height of 40 mm were used. To eliminate the effect of the oxide film formed on the alloy surface, an Al_2O_3 cover was placed above the sample, which was used as a second face surface. The construction of the cover allowed it to move freely along the vertical crucible axis and rotate during torsional vibrations together with it. The measurements of the temperature dependences of viscosity were performed during heating and consequent cooling in the range from the liquidus temperature to 1300 °C. At each temperature before measurements the samples were held for 10 min. The temperature in the viscosimeter furnace was determined with the wolfram–rhenium thermocouple with the precision of ± 5 °C and it was maintained on the same level with the help of a high-precision temperature control (HTR) with the precision of ± 0.5 °C. The thermocouple indications were calibrated to the melting temperature of pure metal (Al, Cu, Ni, Co, Fe).

Calculating the viscosity with the help of numerical methods, the equation [15,16] was solved:

$$f(\nu) = \mathrm{Re}(L) + \frac{\delta}{2\pi}\mathrm{Im}(L) - 2I\left(\frac{\delta}{\tau} - \frac{\delta_0}{\tau_0}\right) = 0$$

where I — the inertia moment of the suspended system; δ, τ, δ_0, and τ_0 — the logarithmic decrement of damping and period of vibrations of the suspended system with a sample and without a sample respectively; Re(L) and Im(L) — real and imaginary parts of the friction function L.

The characteristic dimensions of the samples and oscillation parameters in the measurement of viscosity are the mass of the melt under investigation, m ~ 8.0 g; ratio of the height of the sample to the inner radius of the crucible, H/R ~ 1.6–1.8; and oscillation period, τ ~ 4.1 s.

To calculate the error of viscosity measurements we used the method which was described detailed in [15]. The general quadratic mean error in viscosity values determination is no more than 4%. The unit measurement error was no more than 2%.

3. Results

Typical temperature dependences of the viscosity of Al–Fe melts are shown in Fig. 1. Values of the melt viscosity with an iron content of less than 3% (hereinafter, the iron content in the alloy is specified in at.%) monotonically decrease as the temperature increases (Fig. 1a). The temperature dependences of the viscosity of these liquid alloys obtained in the heating and cooling regimes, coincide (no hysteresis is observed). On the temperature dependences of the viscosity of the melts with an iron content from 3.5 to 6.5% hysteresis of the polytherms obtained during heating and subsequent cooling is exhibited (Fig. 1b).

To analyze the temperature dependences of the viscosity the Arrhenius equation was used. The dependences of the viscosity logarithm on the inverse temperature for the investigated Al–Fe melts are shown in Fig. 2. For liquid Al–Fe alloys a low content of the alloying element (up to 1.5%) a deviation of the viscosity polytherms from the Arrhenius equation is observed. Each of these polytherms can be divided into two temperature intervals, in which dependences of the viscosity logarithm on the inverse temperature are described by a linear function (Fig. 2a). The fracture temperature on the approximating curvers (the

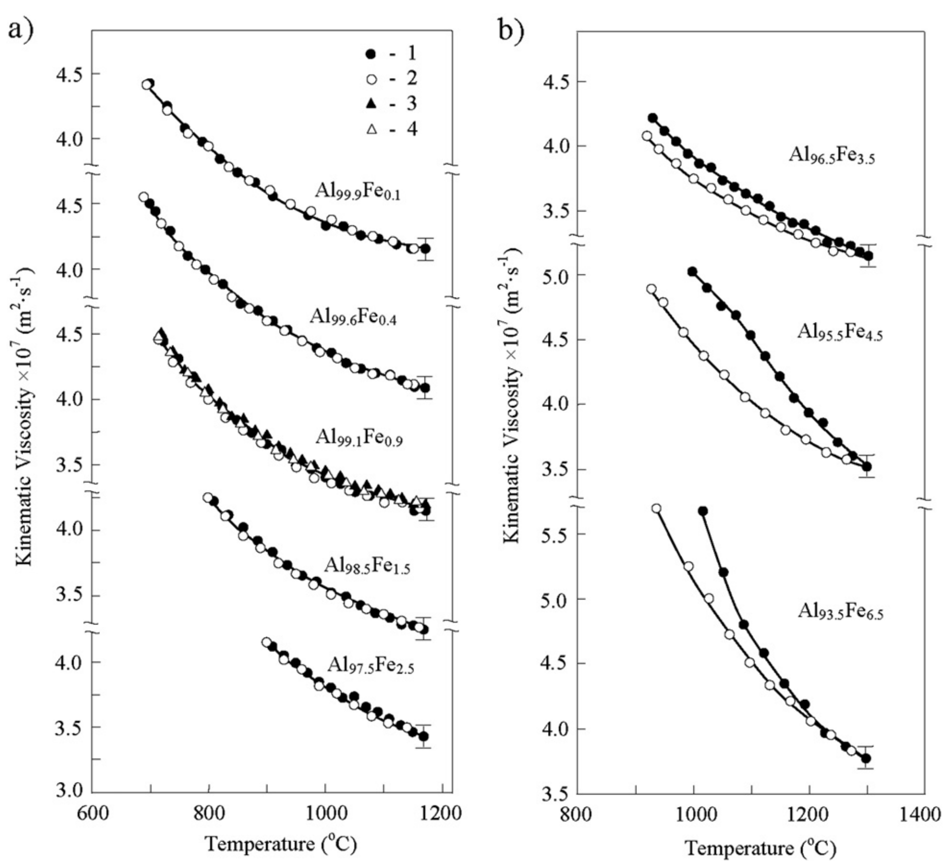

Fig. 1. The temperature dependences of viscosity of the Al–Fe melts: 1 — heating, 2 — cooling, 3 and 4 — repeated heating and cooling, respectively.