AN EXPERIMENTAL INVESTIGATION OF CAPILLARY BREAKUP OF A LIQUID METAL JET

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The limits of influence of oxidation on the capillary breakup of a liquid metal jet is investigated. It is shown that in a region of weak oxidation the disruption of the jet proceeds as is usual for a Newtonian fluid.

The investigation of jet breakup in a liquid metal is interesting in scientific terms because the melt is a fluid with specific properties, and it is interesting in purely practical terms because a series of new technologies may be based upon the principle of a forced capillary jet disruption. At this time, there is a gap in the investigation of metal jet breakup connected, obviously, with the procedural difficulties. There is no systematic investigation covering the entire parameter space. Thus, for example, [1-4] were performed in jets with relatively large diameters, of order 1 mm and larger. In [5], performed in a metal jet with a small diameter ($d_j < 1$ mm), an anomalous regime of melted metal discharge was discovered. In this regime, in an air atmosphere the jet does not break up into drops. We propose that this is connected with the formation on the jet's surface of an oxide film, which damps the oscillation.

The goal of the present work is to determine the boundary of influence of oxidation on capillary breakup of metal jets, and at the same time to investigate the fundamental characteristic processes when oxidation is a weak influence. The experiments were conducted at the facility described in [5]. The experiments used easily melted metals: gallium, tin, and lead. For nozzles we used dies of tantalum and stainless steel with aperture diameters from 30 to 750 μm and with a ratio of length to diameter for the apertures $\ell/d \approx 1$. The experiments were conducted such that aerodynamic force weakly influenced the process, that is, in the regime of axially symmetric capillary jet breakup ($Re < 80Lp^{0.41}$, as in [6]). In conformity with this regime, the speed of the jet never exceeded 15 m/sec. The metal was heated in the crucible above the melting point by amounts ranging from 20 to 200 K. Under such melting, the metal may be considered in the first approximation to be a Newtonian fluid, in as much as its hydraulic resistance while flowing in the channels can be written with well known, accurate dependences for this circumstance [5].

The length of nondisintegrated part of the jet ℓ_n served as a criterion for determining the boundary of influence of oxidation on the disruption of melted metal jets. Measurements were carried out in the following way. The chamber into which the jet flowed was filled with air at a pressure $P = 10^5$ Pa with a known volume concentration of oxygen x_0. The concentration of oxygen was determined using a chemical analyzer, filled with an alkaline solution of pyrogallol. In this case there was a flow regime without the jet's breaking up into drops. Subsequently the air pressure in the chamber was decreased up to the moment of onset of the normal capillary jet breakup, which usually appears for Newtonian fluids. The boundary of the influence of oxidation on the process was determined to be the value of pressure P_b, at which the time average length of the undisintegrated part of the jet was stabilized and did not change for a subsequent decrease of pressure. With allowance made for the initial volume concentration of oxygen x_0 by pressure P_b, boundary value of the volume concentration of oxygen x_b may be determined in mixtures with an inert gas under the pressure P_m. That is, $x_b = kx_0(P_b/P_m)$, where k is the coefficient, allowing for the decrease of oxygen diffusion onto the surface of the jet when the chamber with dissociated air is filled ($P = P_b$) with an inert gas up to a pressure P_m. By employing helium for the inert gas under a pressure of $P_m = 10^5$ Pa we used the experimentally obtained value k = 4.5. We must note that under spontaneous jet disruption the length of its undisintegrated part does not have a constant size, but pulsates in time around its average value in the vicinity of up to ±10%.

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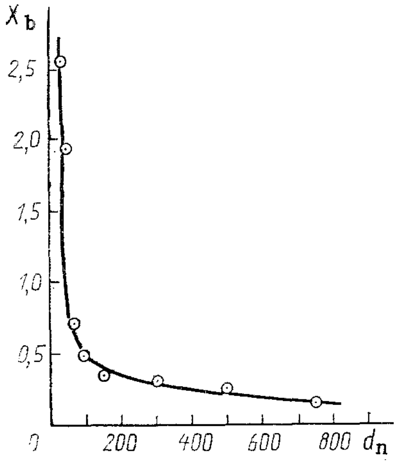

Fig. 1

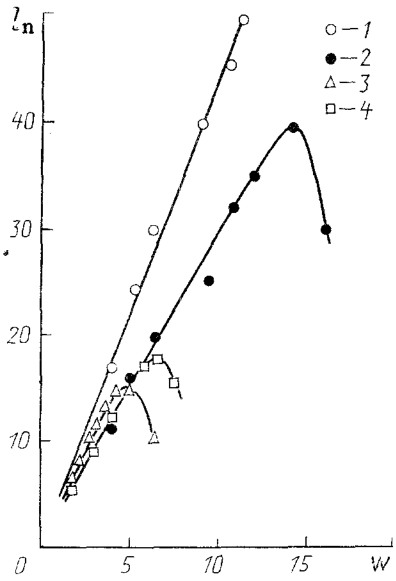

Fig. 2

Fig. 1. Dependence of the boundary of concentration of oxygen x_b (vol. %) upon the diameter of the nozzle opening d_n (microns) in a mixture with an inert gas under the conditions P = 0.1 MPa for a gallium stream. The points are experimental values and the continuous line is a smoothed curve.

Fig. 2. Dependence of the length of the nondisrupted part of the liquid jet ℓ_n (mm), flowing out of an aperture with diameter 150 μm, upon the speed of the jet W, m/sec. Here curve 1 is for ethyl alcohol, 2 is for water, 3 is for tin, and 4 is for gallium.

The boundary of influence of oxidation on capillary liquid metal jet disruption was investigated as a function of the following factors: metal temperature, diameter, and speed of the jet. The dependence of the boundary of concentration of oxygen upon the diameter of the opening of the nozzle, found in a mixture with an inert gas at a pressure $P = 10^5$ Pa, is presented in Fig. 1 for the case of spontaneous gallium jet disruption.

As is visible from the drawing, for the case that the diameter of the jet decreases under otherwise equal conditions, the quantity x_b increases. An analogous dependence appears also for other metals. This form of the dependence of the boundary concentration of oxygen upon the diameter of the jet may be qualitatively explained by consideration of the capillary and of the elastic force, the ratio between which determines the character of the jet disruption. The capillary force, inducing the jet disruption, is related to the jet's diameter by the proportion $F_1 \sim 1/d_j$. The elastic force, originating during deformation of the oxide film and inhibiting it, depends upon the thickness of the film, which in turn is connected with the concentration of oxygen ($F_2 \sim \delta \sim x$). As $x \to 0$, the capillary forces dominate and the oxidizing of the jet's surface does not influence the jet's disruption. For large oxygen concentrations, the capillary forces do not play a substantial role and the growth of perturbations along the length of the jet is suppressed by elastic forces. The beginning of substantial influence of oxidation upon the process occurs when elastic forces become comparable with capillary ($F_2 \approx F_1$). From that it is obvious that the boundary value of oxygen concentration must be increased for larger jet diameters. It follows that in the first approximation (with an error of ±40%) the measurements of the value x_b can be written with a dependence of the type $x_b \sim 1/d_n$.

The dependence of the limiting value of oxygen concentration upon other factors is substantially weaker. Thus, for example, when the temperature of the metal is increased to 200 K, a decrease of x_b occurs, but the decrease is merely by 20-30%. The influence of the speed of the jet upon x_b was not recordable.

Under conditions of weak influence of oxidation ($x < x_b$) it was possible to compare the characteristics of a spontaneous disruption of the liquid metal jet and that of the usual

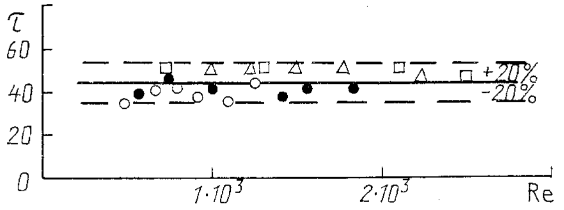

Fig. 3

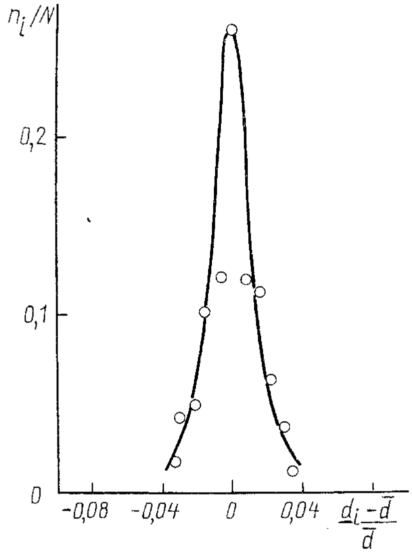

Fig. 4

Fig. 3. Dimensionless time of spontaneous jet breakup. The symbols are the same as in Fig. 2.

Fig. 4. Size distribution of lead granules with an average diameter of 150 microns (points – measurement result; solid line – smoothed curve.

Newtonian fluid. In Fig. 2 are shown the results of measurements of the length of the undisrupted part of the jet for discharge streams of tin, of gallium, of water and of ethyl alcohol from a nozzle with diameter 150 μm. It can be seen that the character of the dependence upon jet speed of the length of the undisrupted part of the jet during spontaneous disruption for all liquids is identical. A linear dependence of $\ell_n(W)$ upon the speed is observed up to the speed approximately corresponding to the critical Reynold's number: $Re_{cr} = 2300$. For a further increase of the speed, corresponding to a transition to the turbulent regime of flow, the length of the undisrupted part of the jet decreases. In the case of a flow of an alcohol jet, the decreasing branch of the curve $\ell_n(W)$ was unobtainable, because the region of speed, corresponding to Re = 2300, was located in conditions of strong aerodynamic action on the jet, that is, a kink instability of the jet. The separation of the curve $\ell_n(W)$ for different liquids is connected with the difference of their physical properties. If one reduces the time of jet disruption to the dimensionless form $\tau = (\ell_n/W)/\sqrt{8\sigma/\rho d^3}$, then for all liquids on the linear portion of the curve $\ell_n(W)$ this time is a constant quantity to a precision of ±20% (Fig. 3). Therefore it follows that the average value of τ for all liquids corresponds with results of the messurements carried out in water in [7].

When an harmonic perturbation was imposed onto the jet, for all investigated metals for $x < x_b$, a transition to the regime of forced capillary disruption into drops of a single size occurred. The optimal perturbation wavelength corresponds to the formula [8] obtained for ordinary Newtonian fluids:

$$\lambda_{opt} = \pi d_j \sqrt{2 + \sqrt{\mu^2/2\sigma\rho}}.$$

For the conditions investigated in the present work this formula may apply in the nonviscous approximation, as well as applying in the slightly viscous case. When the frequency of perturbation of the metal jet deviated from optimal as well as in the case of ordinary Newtonian fluids, disruption of the jet with "satellite" droplets occurred.

These investigations showed that in the region of weak influence of oxidation, it is possible to use the method of forced capillary disruption to obtain high quality monodispersive spherical granules. This is illustrated in Fig. 4, in which is shown the size distribution of lead granules with an average diameter of 150 microns. The distribution in dimension is obtained from measurements on N = 200 randomly selected granules. The dispersion in diameter did not exceed 1.5%, and the asphericity did not exceed 0.5%.

Thus, these investigations allowed the determination of the boundary of substantial influence of surface oxidation of a jet on its disruption. In the region of weak influence of oxidation, it is shown that the processes of the disruption of a liquid metal jet and of an ordinary fluid are similar.

NOTATION

μ, σ, ρ, dynamic viscosity, surface tension, and the density of the liquid, respectively. The quantity $Re = \rho W d/\mu$ is the Reynold's number, W is the jet's speed, and $Lp = \rho\sigma d_j/\mu^2$ is Laplace's number.

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INDUCED CAPILLARY JET BREAKDOWN

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A model is proposed for the induced capillary breakdown of a liquid jet with small surface tension and viscosity, on the basis of numerical solution of the quasi-one-dimensional equations of jet flow. The algorithm employed permits the description of flow from the source to the point of breakdown.

The mathematical modeling of capillary jet breakdown has a rich history, beginning with studies of the capillary instability of a liquid cylinder [1, 2]. Induced breakdown taking account of the mechanism of jet excitation was first described in [3, 4]. Two basic trends in the mathematical modeling of induced jet breakdown have their origin in [4]. The first, based on perturbation theory, was developed in [5-13]. Common to these studies is the solution of hydrodynamic equations in the form of asymptotic series in which 2-3 terms are retained. As a rule, the relative change in jet radius is used as the small parameter. Formulas are obtained for the jet length from the source to the point of breakdown, a qualitative description of the process of satellite formation is proposed [8, 10], and the satellite masses are calculated [9]. The basic deficiency of such work is that the region of applicability of the asymptotic solution is limited to the initial section of the jet, where the perturbation is sufficiently small. In fact, the series may be regarded as asymptotic if the subsequent terms are small corrections to the first terms. Otherwise, it is impossible to discard all but the first few terms. Close to the point of breakdown, none of the initial approximations employed is close to the accurate solution. Therefore, the most interesting processes of drop formation and satellite formation characterized by a large perturbation amplitude are only qualitatively described.

The other trend, which is based on numerical methods, is represented by [14-16]. The numerical solution of the complete hydrodynamic equations in a jet is fairly complex and requires considerable machine time. In [15], such calculations were undertaken for the case of very large flow rates (Weber number We ~ 10,000), when the surface tension is insignificant. This simplifies the calculation, but necessitates taking complete account of the dependence of the velocity and pressure on the radial coordinate. Calculations show that, for a jet at moderate velocity (We ~ 100-500), in a number of cases, quasi-one-dimensional de-

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