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Breakup behavior of a molten metal jet

Yong Suk Oh [a], Dong Yun Choi [a], Jae Yeol Son [b], Bo Young Kim [a], Hyun Wook Kang [a], Cheong Bong Chang [a], Jeong-Tak Moon [b], Hyung Jin Sung [a,*]

[a] Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
[b] MK Electron Co. Ltd., 316-2, Cheoin-gu, Yongin, Gyeonggi-do 449-812, Republic of Korea

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ABSTRACT

The breakup behavior of a molten metal jet into a still gas was studied numerically. Droplet formation was modeled by imposing a sinusoidal waveform perturbation or an amplitude-modulated waveform perturbation. The effect of the temperature on the jet breakup behavior was examined by modeling the liquid metal properties, including density, viscosity, and surface tension, as a function of the temperature. The process by which a molten metal jet was ejected from an orifice exit was modeled to include the wetting of the molten metal on the orifice surface at the gas interface using a dynamic contact angle (θ_D). The effects of the oscillation amplitude (A = 0.10–0.30), the Strouhal number (St = 0.20–0.50) and the Weber number (We = 11.63–129.19) were studied. The imposition of a periodic perturbation yielded linear or nonlinear breakup behavior in the molten metal jet. The conditions found to be optimal for the continuous generation of uniform droplets were identified by optimizing the uniformity of the main droplet, the regular distance between main droplets, the presence of satellite droplets, and the coalescence of the droplets due to surface instabilities and hydrodynamic interactions. The effects of the modulated amplitude (B) and the frequency ratio (N) on the coalescence and separation of neighboring droplets were examined.

1. Introduction

Molten metal jets are potentially applicable in practical industries such as metal powders (Passow et al., 1993), metal sprays (Ünal, 1989; Srivastava et al., 2004), metal coatings (Aziz and Chandra, 2000), and micro-scale metal structures (Yamaguchi et al., 2000). Micro-scale metal sold balls, in particular, are a fantastic packaging technology for preparing low-cost, high-speed, rapid-input/output complex integrated circuit devices prepared from small components. As with inkjet printing applications, molten metal jet systems can be characterized as drop-on-demand or continuous mode generation systems (Liu and Orme, 2001; Takagi et al., 2006). The drop-on-demand mode can produce individual droplets if a target substrate is appropriately positioned. The molten metal droplets in a drop-on-demand printing system are formed by the volumetric change in the fluid induced by applying a voltage pulse to a piezoelectric actuator or a heat pulse to form a vapor bubble. The continuous mode droplet generation system can be used to manufacture solder balls for bonding assemblies in semiconductor packaging as well as for directly printing onto a substrate with high-speed deposition and precise control. A molten metal jet subjected to a periodic disturbance breaks into uniform droplets as a result of the surface tension properties. It is vital to maintain a stable and consistent stream of droplets if a repeatable performance is to be achieved in a continuous mode system.

The mechanism underlying continuous jet breakup into a series of droplets has been studied for more than a century. Plateau (1873) found that a jet tends to break into equal segments (longer than 2π times the jet radius) and form spherical droplets to minimize the surface energy. Rayleigh (1879) investigated the breakup behavior of a laminar liquid jet with a uniform velocity and found that the growth rate of the liquid jet depended on the wavelength and reached a maximum value for a disturbance wavelength greater than the jet circumference. Weber (1931) analyzed the effects of the liquid viscosity and the density of the ambient fluid on the jet breakup process. As Weber's prediction did not agree with the experimental results, Sterling and Sleicher (1975) modified Weber's analysis with a fit to the experimental data. Arai and Amagai (1999) experimentally showed that a laminar jet breaks up due to instabilities in the surface wave at low velocities. Pan and Suga (2006) investigated the hydrodynamic instabilities that occur on the surfaces of liquid jets ejected into a still gas (liquid/air density ratio of about 10^3) using the level set method.

* Corresponding author. Tel.: +82 42 350 3027; fax: +82 42 350 5027.
E-mail address: hjsung@kaist.ac.kr (H.J. Sung).

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The breakup behaviors of liquid jets were classified according to the velocity of the liquid jet in various regimes, including the Rayleigh regime, the first wind-induced regime, the second wind-induced regime, and the atomization regime (Ohnesorge, 1936; Lin and Reitz, 1998). In the Rayleigh regime, an asymmetric liquid jet was observed during breakup into droplets as a result of surface instabilities. The sizes of the droplets generated by the breakup of the liquid jet generally exceeded the orifice diameter. As the jet velocity increased, the breakup length increased in a continuous manner; however, the breakup trend in a laminar jet differed dramatically if the droplet size was smaller than the orifice diameter. The breakup length of a high-velocity turbulent jet was found to be very short. The criterion used to classify these regimes is the breakup length, L_j (Leroux et al., 1997). Sallam et al. (2002) summarized the mean breakup length of a liquid column during the transition from a laminar to a turbulent breakup mode.

Many studies have examined the conditions required to generate uniform droplets and to control the droplet size via the breakup of a liquid jet under applied sinusoidal oscillation (Hilbing and Heister, 1996; Kalaaji et al., 2003). The liquid jet breaks into two types of droplet: main and satellite. These nonlinear motions of the liquid jet were studied using a theoretical model (Chaudhary and Redekopp, 1980; Mansour and Lundgren, 1990). Orme and Muntz (1990) showed experimentally that a droplet stream undergoes a systematic merging process in which droplet formation and separation are controlled by amplitude-modulated disturbances. The amplitude-modulated waveform facilitates the coalescence and separation of droplets by controlling the droplet size due to velocity variations. Two adjacent droplets of silicone oil (Dow-Coning, DC-200) merged at the half-wavelength point to form a large droplet under vacuum conditions ($\sim 10^{-5}$ Torr) as a result of the velocity variations introduced by modulating the amplitude over long travelling distances (about 6 m); however, these conditions are not suitable for preparing molten metal jets because the molten metal tends to solidify rapidly. The wettability of liquid-gas system can considerably affect the surface wave of the jet due to the change of dynamic contact angle on the orifice surface. The analysis of dynamic contact angle was demonstrated by several empirical models (Bracke et al., 1989; Seebergh and Berg, 1992; Jiang et al., 1979) as well as a theoretical model (Blake, 1993). Bussmann et al. (1999), Liu et al. (2005), and Yokoi et al. (2009) expressed their models as a function of the velocity of contact point to compete with the complicated fluid behavior in the vicinity of a moving contact point.

The aim of the present study was to numerically investigate the breakup behavior of a molten metal jet excited with a sinusoidal waveform or an amplitude-modulated waveform. The breakup behavior was investigated by varying the temperature, which tuned the liquid properties. The ejection of the molten metal jet from an orifice exit was accompanied by the wetting of the molten metal onto the orifice surface at the gas interface, which was modeled by introducing a dynamic contact angle (θ_D). The molten metal jet breakup process conducted under a sinusoidal perturbation was investigated by varying the oscillation amplitude (A = 0.10–0.30), the Strouhal number (St = 0.20–0.50), and the Weber number (We = 11.63–129.19). As the droplet formation process underwent coalescence and separation due to surface instabilities and hydrodynamic interactions, the influence of the amplitude-modulated waveform (which was varied by modulating the amplitude (B) and the frequency ratio (N)) was investigated. The droplet stream underwent a complex but systematic coalescence and separation process during the amplitude modulation processes.

2. Problem formulation and numerical method

The breakup behavior of a molten metal jet was examined in an effort to control the droplet formation process using conventional sinusoidal waveforms or an amplitude-modulated sinusoidal waveform. A liquid metal with a given mean velocity flowed through an orifice into a still air volume on the other side of the orifice under atmospheric pressure. A schematic diagram of the molten metal jet is shown in Fig. 1. The molten metal jet may be controlled by varying the jet velocity (V_j), amplitude (A), and frequency (f) of the sinusoidal oscillation. Under these conditions, the breakup behavior may be characterized according to the following non-dimensional numbers: the Reynolds number (Re), the Weber number (We), and the Strouhal number (St),

$$Re = \frac{\rho_l V_m D_o}{\mu_l}, \quad We = \frac{\rho_l V_m^2 D_o}{\sigma}, \quad St = \frac{f D_o}{V_m}, \tag{1}$$

where ρ_l is the density of the liquid, μ_l is the dynamic viscosity of the liquid, σ is the surface tension of the liquid, D_o is the orifice diameter, and V_m is the mean velocity (jet velocity) at the orifice

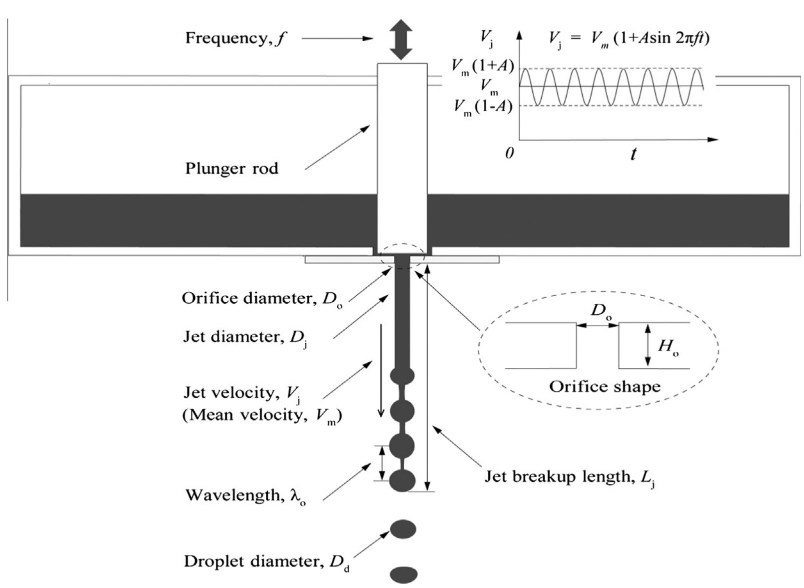

Fig. 1. Schematic diagram of the molten metal jet and orifice shape.