Recent Progress in Droplet-Based Manufacturing Research

H.-Y. Kim, J.-P. Cherng, and J.-H. Chun

Abstract— **This article reports the recent progress of research made in the Droplet-Based Manufacturing Laboratory at MIT. The study has been focused on obtaining a fundamental understanding of microdroplet deposition and applying the technology to various practical applications. Specific scientific contributions include the development of an analytical model for droplet splashing/recoiling, an in situ droplet size control methodology, and a study of microstructure design for spray forming. The research performed in the lab provides both fundamental knowledge base and practical process developments for a range of manufacturing applications, including electronics packaging, spray forming and freeform fabrication.**

Keywords— **Droplet-Based Manufacturing, Microdroplet deposition, Electronics packaging, Freeform fabrication.**

I. INTRODUCTION

THE research performed in the Droplet-Based Manufacturing Laboratory at MIT aims to obtain a fundamental understanding of microdroplet deposition in the Uniform Droplet Spray (UDS) process for a range of manufacturing applications, including electronics packaging, spray forming and freeform fabrication. The UDS process produces droplets of uniform size by breaking up a liquid metal jet with high-frequency, mechanical vibration. The droplets are electrically charged to the same polarity to prevent in-flight merging. The uniformity of the droplet size allows for systematic studies of key parameter effects. The UDS process has been proven to produce metal alloy droplets of tin, zinc, aluminum, and copper as well as waxy droplets ranging from 75 μm to 800 μm in diameter. The process can be scaled from a single droplet stream to multiple streams depending on desired mass flux. The research areas pursued in this period are droplet spreading behavior upon impact with a solid surface, an on-line droplet-size control system, a droplet deflection system, and deposit thermal state modeling.

II. RESEARCH FINDINGS

This study has been intended to obtain a fundamental understanding of microdroplet deposition in the UDS process and apply the technology to various manufacturing applications.

This study has accomplished or produced:

- a fundamental study of microdroplet deposition behavior
- an on-line, closed-loop droplet size control system
- a droplet trajectory control system
- a study of deposit thermal state in spray forming

The results obtained in each of the above four areas are briefly described below.

A. Droplet Deposition Behavior

Our study of droplet deposition behavior has addressed splashing, oscillation, and bouncing phenomena. A linear perturbation theory is developed to investigate the interface instabilities of a radially-expanding, liquid sheet in cylindrical geometries. The theory is applied to rapidly spreading droplets upon collision with a solid surface as the fundamental mechanism behind splashing. The analysis is based on the observation that the instability of the liquid sheet, i.e., the formation of the fingers at the spreading front, develops in the extremely early stages of droplet impact. The shape evolution of the interface in the very early stages of spreading is numerically simulated based on the axisymmetric solution obtained by a theoretical model. The effects of factors, such as the transient profile of an interface radius, the perturbation onset time, and the Weber number, on the analysis results are examined. This study shows that a large impact inertia, associated with a high Weber number, promotes interface instability and prefers high wave number for maximum instability. As shown in Fig. 1, the splat shape and numbers of fingers at the spreading front of droplets predicted by the model agree well with those experimentally observed.

Although the droplet spreading phenomena have been extensively studied in the past, the subsequent recoiling phenomena, which strongly influence the ultimate impact behavior of molten metal droplet, have not been systematically investigated. In this work, a high-speed imaging system was used to study the droplet recoiling and bouncing behavior (see Fig. 2). The temporal evolutions of the base diameter of the recoiling droplets were measured from the images. The results were in good agreement with an approximate model developed based on the variational principle, as shown Fig. 3. Figure 3 also illustrates that droplets deposited on poor-wetting surfaces recoil faster. Furthermore, analysis showed that the relative magnitudes of surface energy and viscous dissipation play critical roles in determining droplet dynamics.

Under certain conditions, liquid metal droplets deposited on substrates do not stick to the surfaces but rather, they bounce off. The high-speed images in Fig. 2 reveal that bouncing is a very violent form of droplet oscillation. To determine the conditions for bouncing and sticking, an empirical regime map is constructed using two characteristic time scales and extensive experimental data for pure Sn droplets. As shown in Fig. 4, a clear trend develops: bounc-

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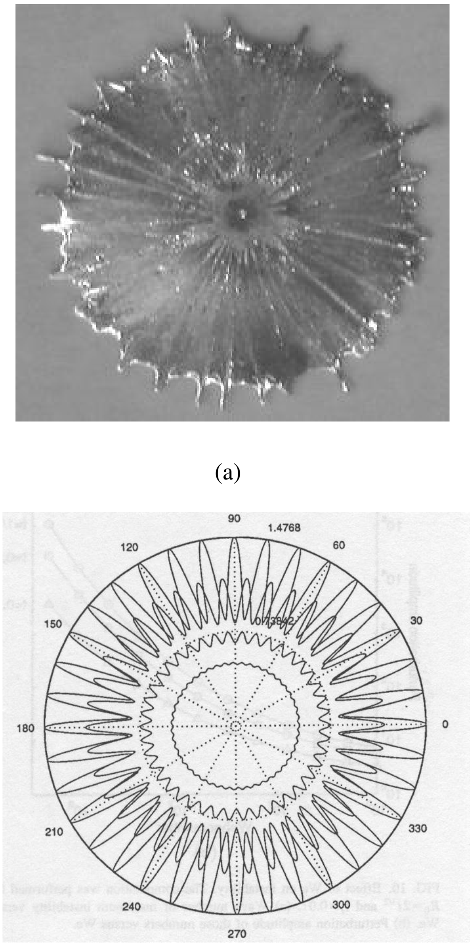


Fig. 1. (a) Splashed tin splat shows development of spreading fingers. (b) Simulated splat shape evolution.

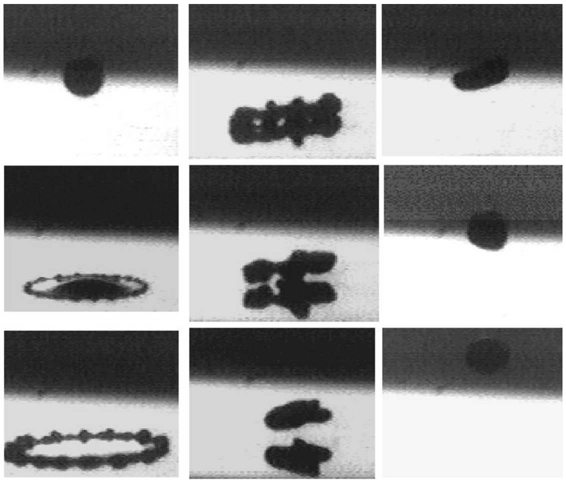


Fig. 2. Images of molten tin droplets bouncing off the stainless steel 304 surface. Original droplet diameter = 1.67 mm, Impact velocity = 3.08 m/s, Droplet temperature at impact = 263^{o}C, Target temperature = 195^{o}C.

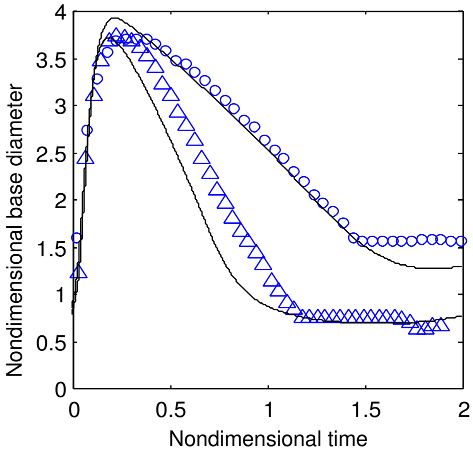


Fig. 3. The experimental measurements of the temporal evolution of the base diameter of water droplets agree with model predictions. Triangles denote the polycarbonate surface and circles the silicon oxide surface.

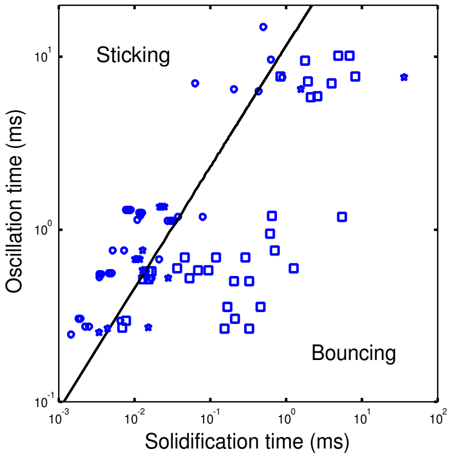
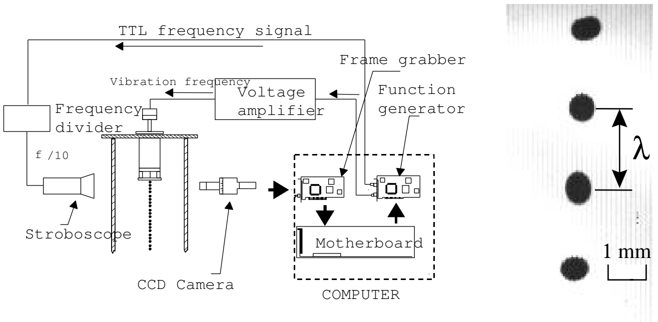


Fig. 4. Regime map of bouncing and sticking for molten Sn droplets on non-wetting surfaces. Squares denote bouncing conditions, circles sticking conditions. Pentagrams designate the Sn droplets deposited on a solid Sn substrate.

ing occurs when solidification is slow compared to oscillation when a droplet collides with a non-wetting surface. The data also suggest that bouncing may be prohibited by good wetting between the droplet and its target, even if solidification is fairly slow compared to oscillation.

B. On-line, Closed-loop UDS Droplet Size Control System

The Uniform Droplet Spray (UDS) process has proven to be an efficient method for the production of mono-sized metal spheres. The UDS process was developed based on the concept of Rayleigh's liquid jet instability. Although the original UDS equipment could produce metal spheres having diameter within ± 3% from the mean, it could only match a mean diameter to a target diameter by a series of trial-and-error experiments. This deficiency led to the development of a high performance closed-loop control system. The technique is elegant because of its simplicity - we measure the wavelength the wavelength of the ligament separation. By applying the mass conservation principles,



(a) (b)

Fig. 5. (a) Uniform Droplet Spray control system. (b) Actual image of 760 μm drops.

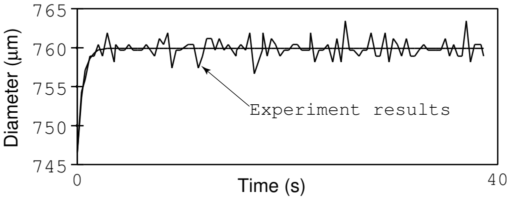


Fig. 6. Step response.

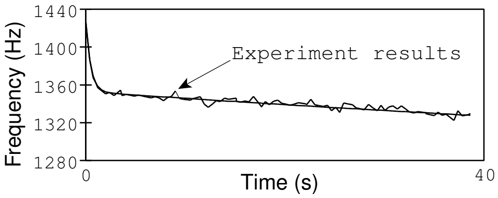


Fig. 7. Control input profile.

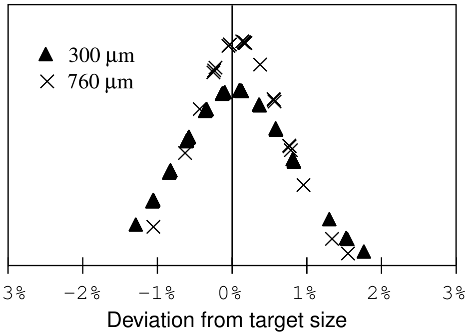


Fig. 8. Normalized sphere diameter distribution.

we are able to determine the diameter of the spherical powders. A simple integral controller is then employed to adjust the ligament break-up frequency to control the powder size.

Figure 5 shows a schematic representation of the vision-based control system. The image of the UDS droplets is acquired using a CCD camera with a zoom lens. A stroboscope lamp flashes at 1/10 the frequency at which the droplets are generated. The strobe flash freezes the droplets in space so the system can acquire a clear image. The video signal is sent to the frame grabber card. An image-processing algorithm calculates the distance between the droplets from the acquired image and determines the actual droplet size produced. The controller will then adjust the vibration frequency to compensate for variations away from the target droplet size.

Figure 6 shows the step response of the system. Figure 7 shows the control input profiles. One of the lines represents the actual response of the system and the other line represents the simulated response. Figure 8 shows the results of a statistical analysis performed on the experimental result shown in Figs. 6 and 7. For each experiment, 250 randomly selected solder spheres were measured using an optical microscope to determine the mean and variance of the actual distribution. The diameter measurements were estimated to be accurate within $\pm 1\mu$m. On the basis of the statistical analysis, almost all of the spheres produced in the experiments were found to have a variation of less than 3% from the target diameter.

C. Droplet Deflection System

The UDS system produces thousands of droplets per second during its operation. In order to observe the droplet impact and deposition behavior in real-time, it is necessary to reduce the number of droplets that will pass through the camera view zone at any given time. One of the most efficient ways to reduce the number of droplets in spray stream is to deflect most of them away at a set interval. The ability to selectively deflect and deposit droplets at different locations is also valuable in the applications of UDS to rapid prototyping and electronics packaging.

A droplet deflection system was developed to deflect droplets away from the spray stream at precise intervals (see Fig. 9). The system was fabricated and the test results indicated that a useful amount of droplet deflection can be achieved (Fig. 10). The degree of separation between the deflected and undeflected streams of droplets was modeled and the prediction was compared with experimental results. This comparison revealed that the degree of actual deflection was approximately twice as high as the predicted value. Using the trajectory controller, deposition was conducted using pure tin as the droplet material. A low frequency deposition at 57 Hz produced a vertical pillar, whereas a high frequency deposition at 574Hz resulted in a large solidified drop on the substrate. Further development works are required to incorporate a high-speed vision system to capture droplet images and to explore the droplet delivery capability for rapid prototyping applications.

D. Microstructure design for spray forming

Another application of the UDS process is towards fabricating parts by spraying partially-liquid droplets onto a substrate or mold. The advantage of this process and other spray forming processes over conventional ingot metallurgy techniques is their ability to produce materials directly from the melt with refined grain sizes and reduced phase. In order to control the formation of deposit microstructure,

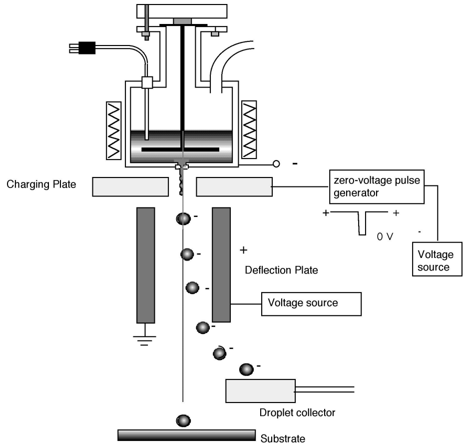


Fig. 9. Droplet trajectory control system.

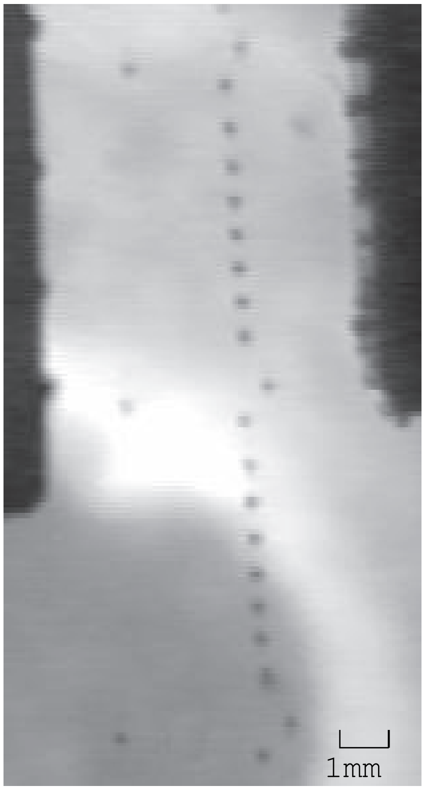


Fig. 10. Image of deflected droplets.

it is necessary to understand the effects of the process parameters and deposit thermal state.

The thermal state of the deposit during and after spray deposition is determined by three factors: the enthalpy flux of the incoming spray, the rate of heat extraction by the substrate, and the rate of heat loss from the top surface of the deposit. A two-dimensional, axisymmetric finite element model has been developed to predict the temperature of the deposit using Zn-20%Sn alloy material. Experiments were conducted with the UDS process for different substrate conditions and compared to the simulation results. The temperature of the top surface of the deposit was measured using a fiber-optic infrared sensor, while the bottom surface was measured using a small-diameter thermocouple.

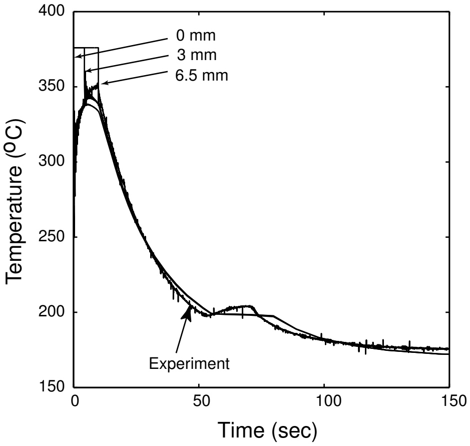


Fig. 11. The experimental measurement of the surface temperature of a Zn-20%Sn deposit sprayed onto a glass substrate at 160^{o}C for 10 seconds is compared to the simulation results for deposit temperature at different heights from the substrate surface.

Figure 11 shows good agreement between the experimental and simulation data for the case of Zn-20%Sn droplets at 376^{o}C sprayed onto a glass substrate at 160^{o}C for 10 seconds. The growth rate of the deposit is determined by measuring the actual deposit height and dividing it by the spray duration. Figure 12 shows the results for the same spray conditions except with a titanium substrate at 175^{o}C. In the latter example, there is greater discrepancy between the simulation and experimental results, probably due to using a greater than actual contact resistance between the deposit and titanium substrate.

It is well established for cast alloys that the local solidification time significantly affects the final scale of its microstructure. Therefore, to determine if such a correlation exists for the UDS process with Zn-20%Sn deposits, the solidification time was obtained from the experimental data and the microstructures of the deposits were examined using scanning electron microscopy. A characteristic feature size was measured for each deposit using the linear intercept method. Figure 13 shows that the local solidification time, t_f, can be related to the final grain size, λ, by $\lambda = 2.1 t_f^{0.4}$. Future work includes testing the robustness of this relationship by varying different process parameters such as droplet temperature and size. If proven, the correlation would allow deposit microstructure to be designed using the deposit thermal state model.

III. Summary

Recent progress in the MIT Droplet-Based Manufacturing Laboratory includes the development of an analytical model for droplet splashing/recoiling, an in-situ droplet size control system and the modeling of deposit thermal state for microstructure design in spray forming. In the droplet splashing study, we show that the interface instabilities of a radially-expanding, liquid sheet in cylindrical geometries is a fundamental mechanism that causes droplet

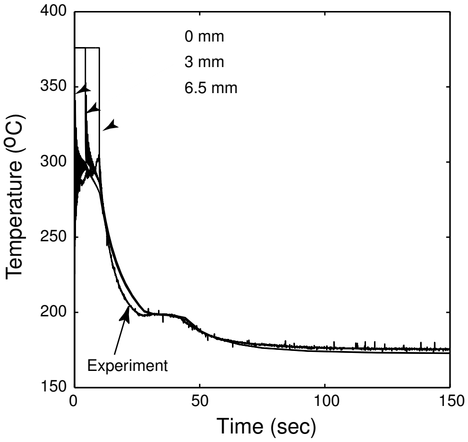


Fig. 12. The experimental measurement of the surface temperature of a Zn-20%Sn deposit sprayed onto a titanium substrate at 175°C for 10 seconds is compared to the simulation results for deposit temperature at different heights from the substrate surface.

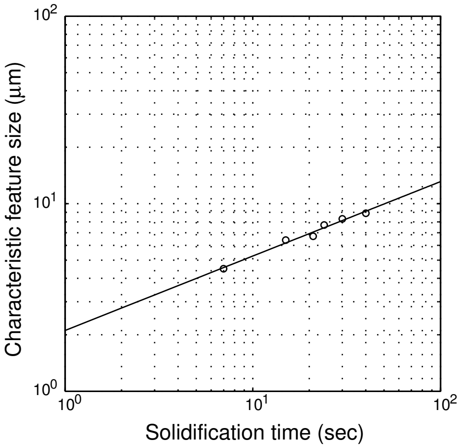


Fig. 13. The empirical relationship between solidification time and characteristic feature size of the Zn-20%Sn deposit microstructure.

splashing. The recoiling behavior of a droplet upon impact was modeled using a variational principle and the analysis results are in good agreement with experimental results. The in-situ droplet size control methodology was devised, which resulted in monosized metal spheres having a variation of less than 3% from the target diameter. A study of deposit thermal state in the spray forming process shows that the two dimensional finite-element model correctly predicts the deposit thermal history. Thus deposit microstructure can be tailored during spray forming using the developed model through thermal state control of the deposit.

Acknowledgment

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