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Introduction

In the uniform droplet spray (UDS) process, a jet of liquid metal is broken up into uniform droplets by applying a periodic perturbation to the jet at a specific frequency and amplitude. The droplets are electrically charged to the same polarity to prevent in-flight merging. As a result of the uniform droplet size distribution, the dynamic and thermal states of the droplets can be precisely controlled in the UDS process. Before the UDS process can be applied to the production of aluminum sheets, the thermal history of the droplets must be understood. The incoming thermal state of the droplets at impact with the substrate significantly affects the degree of droplet consolidation as well as the microstructural grain size, which in turn determine the final material properties of the sprayed part. Therefore, the first step in this research was to simulate and measure the droplet thermal state during flight.

The thermal state of a solidifying droplet is defined by its temperature and volume fraction of solid. To predict the temperature and solid fraction of the droplets as functions of flight distance, a thermal model was developed for aluminum binary alloy droplets by assuming Newtonian cooling, no undercooling, and local equilibrium at the solid/liquid interface during solidification. Experiments to validate the droplet thermal model were made with Al-4.5wt% Cu and Al-4.3wt% Fe droplets, 275 μm and 250 μm in diameter, respectively. The droplets were quenched at different flight distances and their microstructures were examined metallographically using SEM analysis. By observing the change in microstructure from a fully liquid droplet to a fully solid powder, the solid fraction of the droplet as a function of flight distance can be measured.

Summary of Results

In the Al-4.5wt% Cu droplets, two distinct regions of microstructure were observed: a fine crystalline region and a coarser dendritic region, as shown in Figure 1(a). The volume occupied by the coarser dendrites increased with flight distance. Due to the difference between the cooling rate during flight and the cooling rate during quenching, the fine crystalline region was interpreted as the liquid phase in the droplet before impact and the coarser dendrites as the solid phase formed during flight. However, based on this assumption, the experimentally measured solid fractions were consistently higher than the predicted solid fraction. The discrepancy

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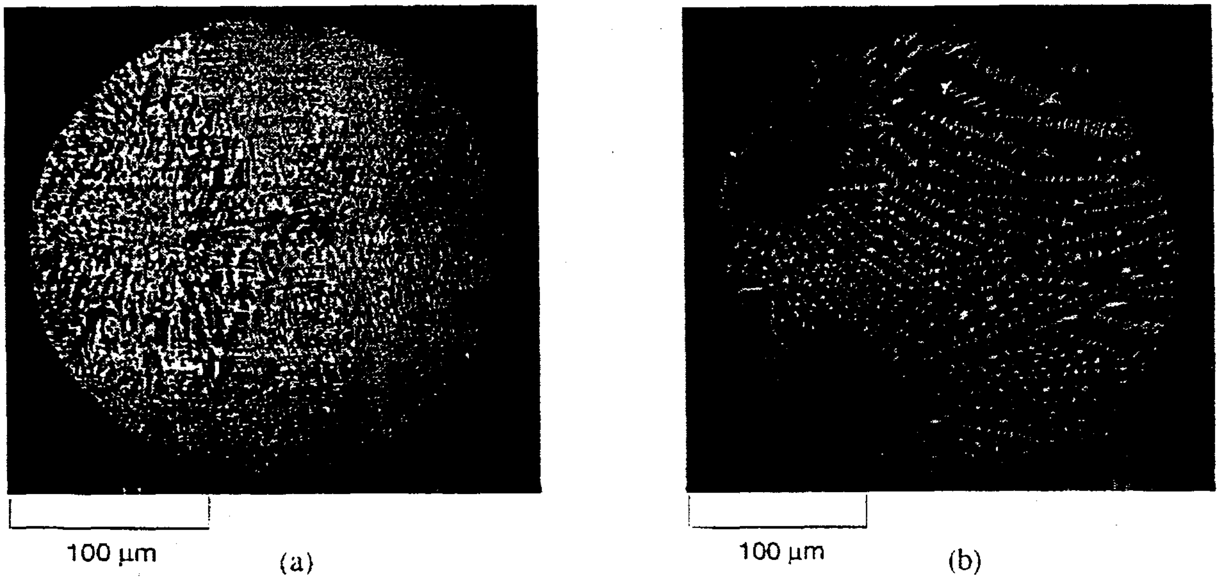

Figure 1. SEM micrographs of (a) 275 µm, Al-4.5wt% Cu quenched droplet and (b) 250 µm, Al-4.3wt% Fe quenched droplet.

suggests that the coarser dendritic region is a mushy zone of liquid and solid phases rather than a fully solid phase formed during flight. Measurement of secondary dendrite arm spacing in Al-4.5wt% Cu powders agreed with the cooling rate predicted by the thermal model.

In efforts to avoid a mushy zone as experienced with the Al-4.5wt% Cu droplets, Al-4.3wt% Fe droplets were tested. Aluminum has less than 0.05% solid solubility for iron. The evolution of microstructure observed in the Al-Fe alloy droplets was considerably different; the droplets exhibited undercooling behavior. Droplets which were allowed to fully solidify during flight revealed completely undercooled microstructure with no dendritic or cellular features. The microstructure of the quenched droplets showed Fe-rich dendrites growing from undercooled featureless regions, as shown in Figure 1(b). This suggests that quenching the Al-Fe droplets in flight interrupts undercooling and forces recalescence to occur on impact, after which the remaining liquid portion cools at a slower rate and produces the dendrites. The Al-Fe droplets were estimated to have undercooled by 100 K.

In conclusion, the data obtained through the droplet quenching method do not substantiate the droplet thermal model for aluminum binary alloys. The mushy zone created during solidification of the Al-4.5wt% Cu droplets prevents accurate measurement of the solid fraction. The undercooling of the 250 µm, Al-4.3wt% Fe droplets is not treated by the equilibrium solidification model. Undercooling can be avoided by using larger diameter droplets for the Al-4.3wt% Fe alloy. Fortunately, this allows the throughput rate of the UDS process to be increased without sacrificing rapid solidification effects.

Future Work

Further work is necessary to validate the droplet thermal model to enable the production of non-porous and homogeneous aluminum sheet products. By using larger diameter droplets of Al-4.3wt% Fe, the droplet quenching method should be successful in measuring droplet solid fraction. Furthermore, this study of undercooling behavior in uniform droplets of the Al-Fe alloy provides a unique opportunity to produce novel deposit microstructures. A more direct method of measuring the thermal state of the droplets as a function of flight distance is currently being developed. Micro-temperature sensors based on the resistive temperature detection (RTD) concept are being fabricated with VLSI technology to provide high spatial and temporal measurement resolution.

After establishing the thermal history of the droplet during flight, the UDS process can then be optimized to spray the aluminum sheets. A multi-nozzle apparatus will be designed and built to increase the throughput rate. Current mass flow rate is approximately 0.25 g/s through one nozzle for 300 μm droplets of aluminum. The mass flux distribution in the spray will be modeled and measured for different multi-nozzle configurations deposited onto a moving substrate. Achieving a uniform deposit profile will be important in producing flat sheet material.

A systematic series of experiments will be conducted to determine the how droplet thermal state, deposit thermal state, and mass flux distribution affect the deposit microstructure and geometry. This information will aid in developing the UDS process for the rapid production of other near-net-shape parts. Unlike other rapid prototyping methods, such as stereolithography, selective laser sintering, and 3-D printing, the UDS process can form metallic parts by manipulating the geometry as well as the microstructure of the sprayed part.

Academic Progress

At the end of January, I passed the doctoral qualifying examinations at MIT and began my Ph.D. studies. In addition to research, I took two graduate courses in mechanical engineering, Industrial Product Design and Management for Engineers. In the coming year, I plan to hold regular thesis committee meetings and submit a paper based on the solidification behavior observed in the aluminum alloy droplets.