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SPRAY-FORMED TOOLING

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ABSTRACT

The United States Council for Automotive Research (USCAR) has formed a partnership with the Idaho National Engineering Laboratory (INEL) to develop a process for the rapid production of low-cost tooling based on spray forming technology developed at the INEL. Phase I of the program will involve bench-scale system development, materials characterization, and process optimization. In Phase II, prototype systems will be designed, constructed, evaluated, and optimized. Process control and other issues that influence commercialization will be addressed during this phase of the project. Technology transfer to USCAR, or a tooling vendor selected by USCAR, will be accomplished during Phase III.

The approach INEL is using to produce tooling, such as plastic injection molds and stamping dies, combines rapid solidification processing and net-shape materials processing into a single step. A bulk liquid metal is pressure-fed into a de Laval spray nozzle transporting a high velocity, high temperature inert gas. The gas jet disintegrates the metal into fine droplets and deposits them onto a tool pattern made from materials such as plastic, wax, clay, ceramics, and metals. The approach is compatible with solid freeform fabrication techniques such as stereolithography, selective laser sintering, and laminated object manufacturing. Heat is extracted rapidly, in-flight, by convection as the spray jet entrains cool inert gas to produce undercooled and semi-solid droplets. At the pattern, the droplets weld together while replicating the shape and surface features of the pattern. Tool formation is rapid; deposition rates in excess of 1 ton/h have been demonstrated for bench-scale nozzles.

INTRODUCTION

Costs and lead times for tool fabrication are significant limiting factors in getting new products to market and garnering a reasonable market share. Nowhere is this more obvious than the American automotive industry, where future regulations and foreign competition will drive tooling costs to new highs unless rapid, low-cost processes are developed. The INEL is developing its spray forming process for automotive injection molding, die casting, and stamping dies, under DOE sponsorship, in support of USCAR programs. The general concept involves converting a part design described by a computer-aided design file to a plastic, ceramic, or metal pattern, via a suitable rapid prototyping process, followed by spray forming a replica of the pattern in the tool-making alloy of choice.

In spray forming, liquid metal is converted to a spray of fine droplets and deposited onto a substrate or pattern to form a near-net-shape solid. Researchers at the INEL have developed a unique spray-forming method to fabricate metals, polymers, metal matrix composites, and polymer matrix composites in net- or near-net-shape [1-6].

Spray deposition with de Laval nozzles typically involves transonic gas/particle flow through the nozzle and subsonic free jet flow from the nozzle to the substrate. The unusually high droplet cooling rates (normally > 10^2 K/s) result in rapidly solidified products that can offer property improvements such as refined microstructures, extended solid solubilities, and reduced macrosegregation compared to cast materials. The process provides economic advantages because the product is near-net-shape and fewer unit operations, such as machining, forging, or rolling, are required.

Properties of the deposit are tailored by controlling the characteristics of the spray plume (droplet size distribution, velocity, heat content, flux, and flow pattern) and substrate (material properties, surface finish, and temperature). Toward that end, an in-flight particle diagnostics system is used to simultaneously measure droplet size, velocity, and temperature in the atomized plume. This system measures particle diameters between 5 and 1,000 μm using an absolute magnitude of scattered light technique. Velocities of 10 to 100 m/s are measured with a dual beam laser Doppler velocimeter; particle temperature is measured with a high-speed two-color pyrometry technique. Modeling the multiphase flow, heat transfer, and solidification phenomena provides guidance for component design and process control.

APPROACH

A schematic of the approach used to produce net-shape tooling is shown in Figure 1. A bulk liquid metal is aspirated or pressure-fed into a spray nozzle, where it contacts high

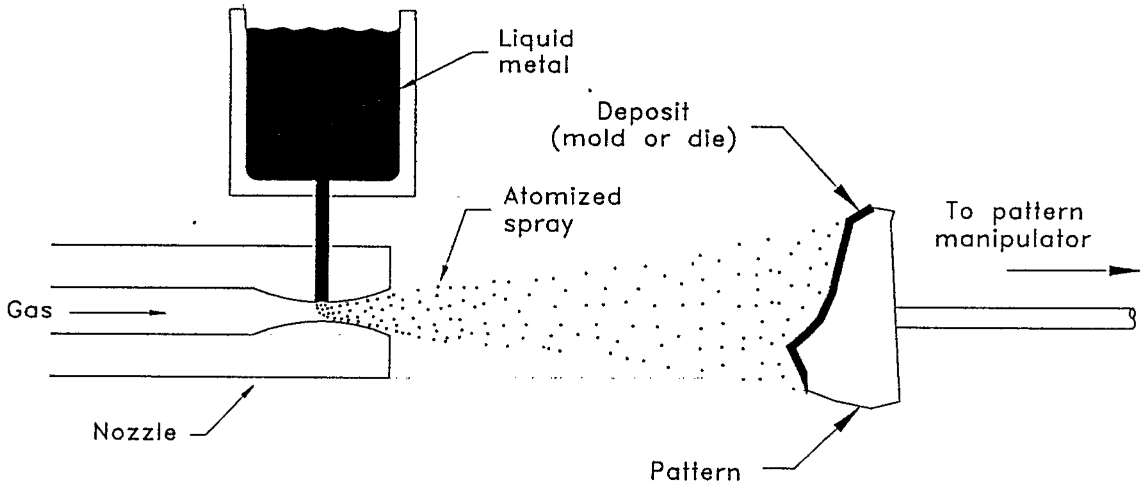


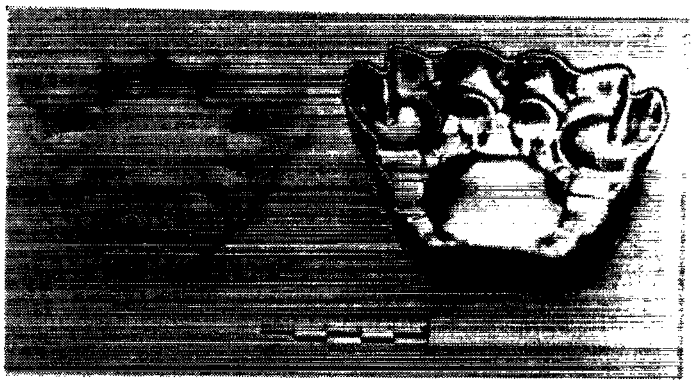
Figure 1: Schematic of tool-forming approach.

velocity, high temperature inert gas. Aerodynamic forces overcome surface tension forces, disintegrating the molten metal into very fine droplets and entraining them in a highly directed spray. Outside the nozzle, the jet entrains relatively cold inert gas. This provides a heat sink for the spray, producing undercooled and semisolid droplets. The droplets are deposited onto a pattern that is manipulated in the jet to provide even coverage. Upon impact, the droplets adopt the shape and surface texture of the tool pattern while forming a coherent solid. The resultant metal shell is cooled to room temperature and separated from the pattern.

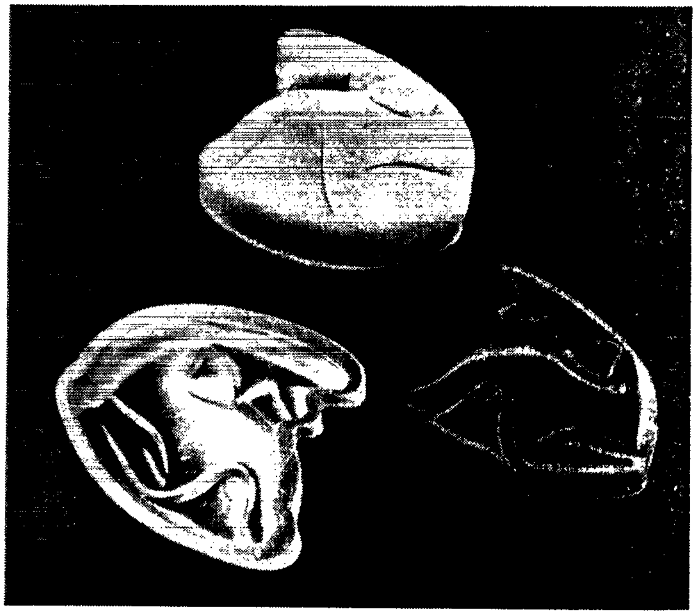
The spray apparatus was designed and constructed in-house. Its main components (spray nozzle, liquid metal reservoir, gas heater, and pattern manipulator) are housed in an inert-gas-purged chamber to limit the detrimental effects of oxide formation. Bench-scale nozzles having transverse throat widths of 17 mm (0.66 in.) have been operated at gas-to-metal mass flow ratios (G/M) as high as 10. Metal throughput has ranged from 7 to 52 kg/h (15-115 lb/h) during the initial deposition stage as the pattern's surface features were replicated. Throughput has then been increased to as high as 900 kg/h (2000 lb/h) until the walls of the mold reached the desired thickness. A variety of commodity thermoplastics and advanced polymers have been used as pattern materials with good results, including low-density polyethylene (LDPE), polypropylene (PP), poly(methyl methacrylate) (PMMA), polycarbonate (PC), nylon 6/6, polystyrene (PS), polyetherimide (PEI), and polyimide (PI). Ceramic and metal tool patterns have also been used.

RESULTS

Examples of spray-formed mold shells are given in Figure 2. Shells of tin (Figure 2a) and a Zn-Al-Cu forming-die alloy (Kirksite, Figure 2b) were produced in about 5 min with a bench-scale nozzle by spray depositing the metal onto LDPE patterns having the shape of sand toys. Replication of surface features, including fine scratches in the pattern, was excellent. Peak-to-valley surface roughness of the shells at the deposit/pattern interface was measured to be as low as 2 μin. using a stylus profilometer.



(a) Tin mold (right) and polyethylene pattern (left).



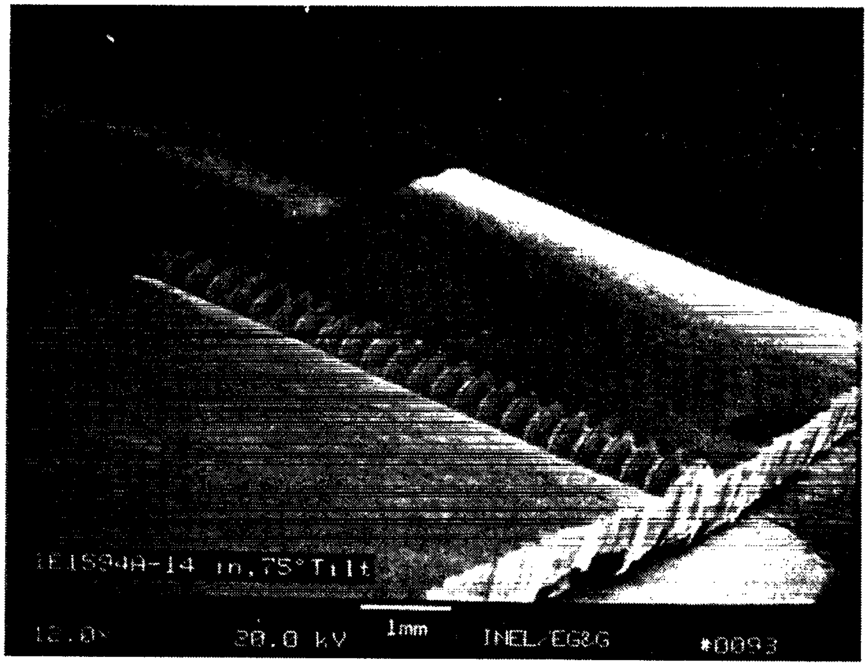
(b) Zn-Al-Cu alloy molds (left and above) and polyethylene pattern (right).

Figure 2: Spray-formed metal molds.

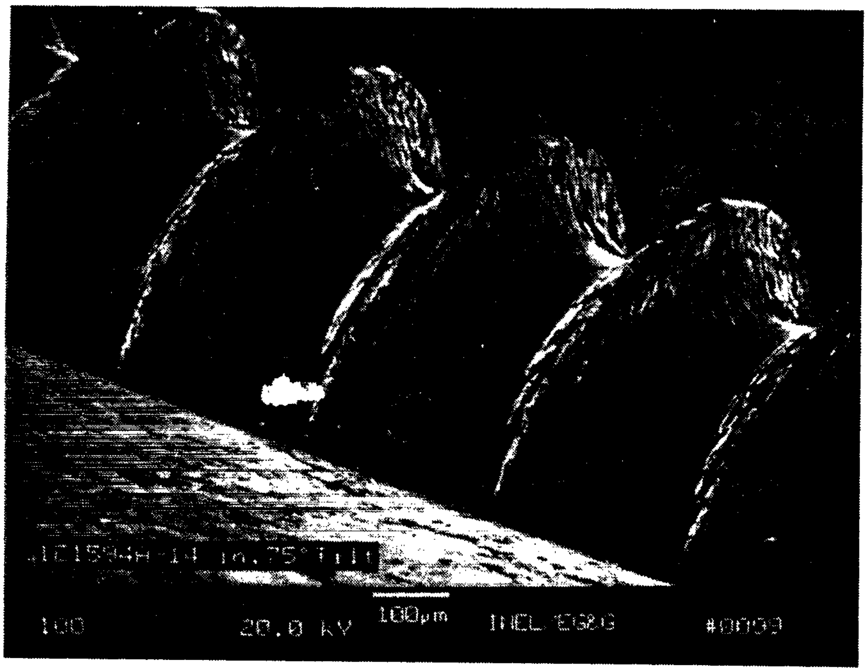
To quantify surface replication, a fine threaded rod (90 threads/inch) was hot pressed into PMMA and removed. Tin was spray deposited onto the "micropatterned" PMMA, detached, and examined using an SEM. The photographs in Figure 3 demonstrate the high degree of surface replication possible with spray forming.

As-deposited tool density, measured by water displacement using Archimedes' principle, has been close to 100% of theoretical for tin alloys. The porosity distribution in a thin-sectioned mold shell is illustrated by the photomicrograph in Figure 4a. There is very little porosity through the thickness of the material. The grain structure of the same material is shown in Figure 4b. The equiaxed grain structure, with an average grain size of 9 μm (ASTM grain size number 10 1/2), is much more refined than that of the cast starting material (Figure 4c) due to rapid solidification.

Kirksite mold shells have been produced using a variety of pattern materials. The liquid metal was heated to 500-600°C and atomized with gas heated to about 550°C. Depending upon conditions, the bulk density of sprayed material is 85 to 98%

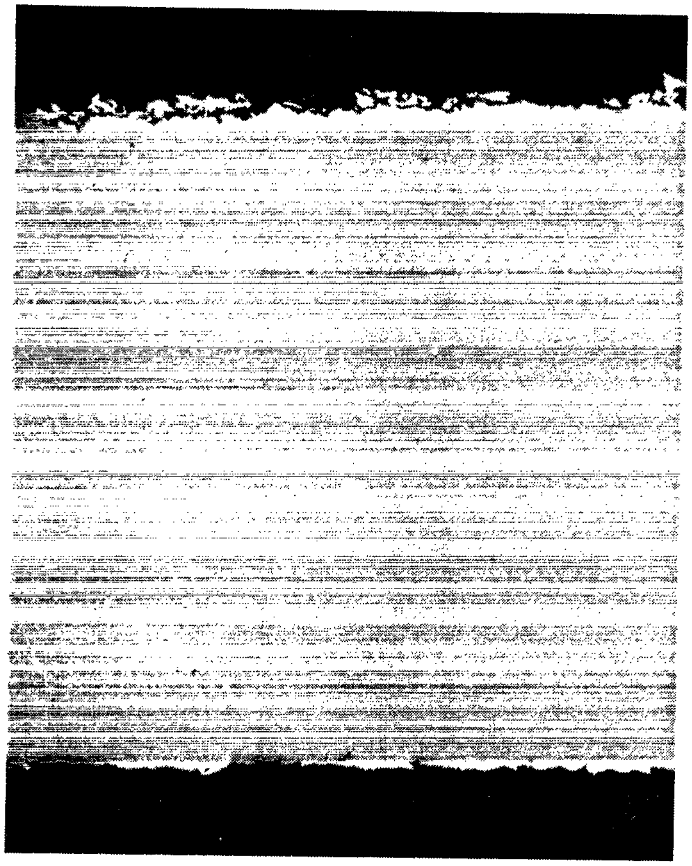


(a) 12X.

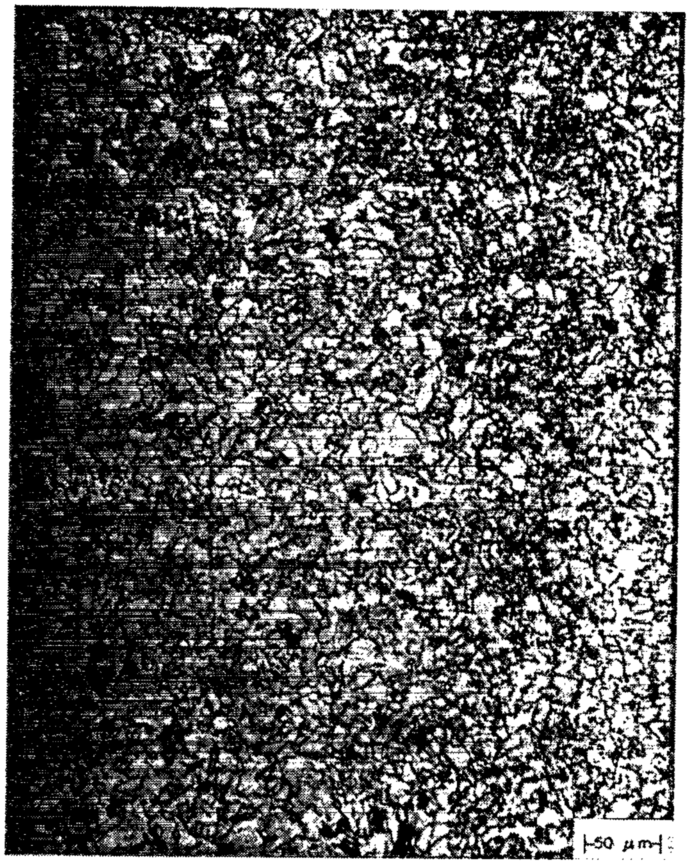


(b) 100X.

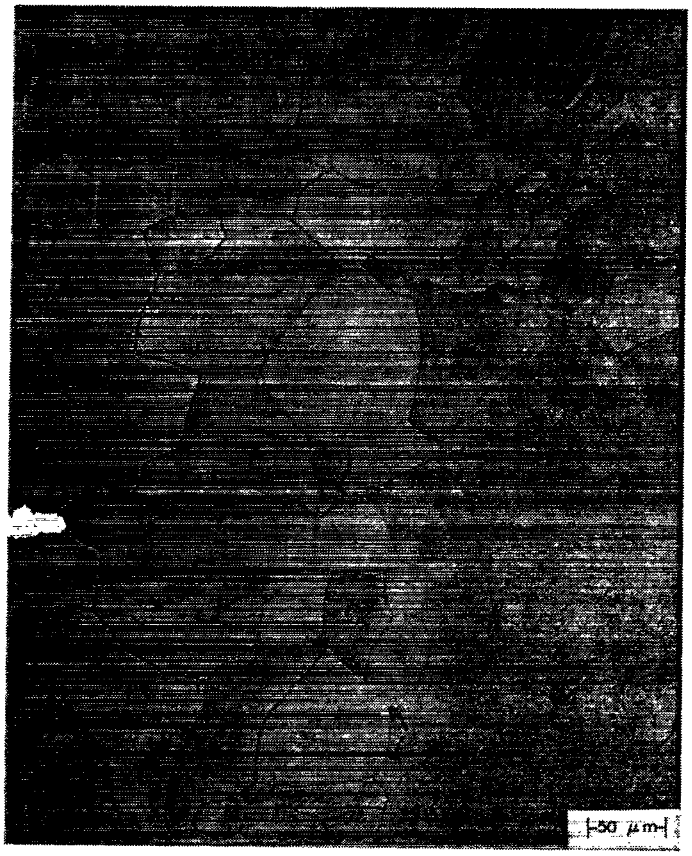
Figure 3: SEM photographs illustrating replication in spray-formed tin of features in micropatterned polymers.



(a) Spray-formed mold, polished.



(b) Grain structure of spray-formed mold.

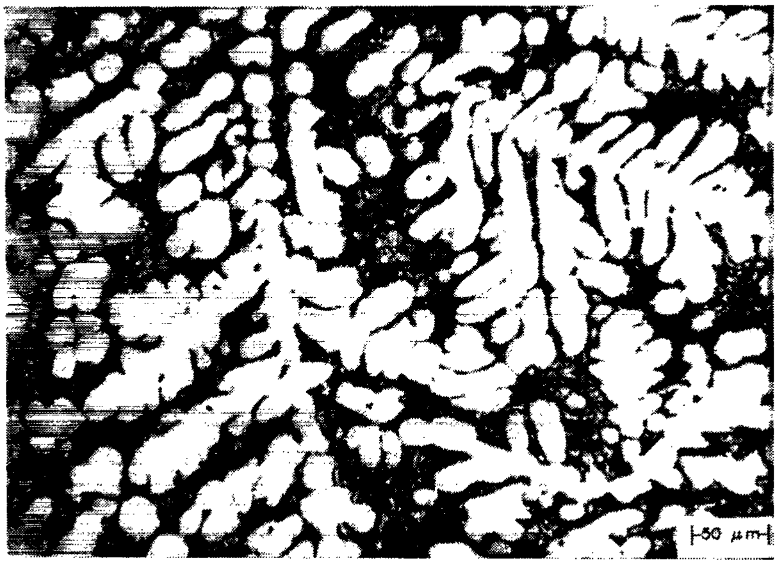


(c) Grain structure of cast metal.

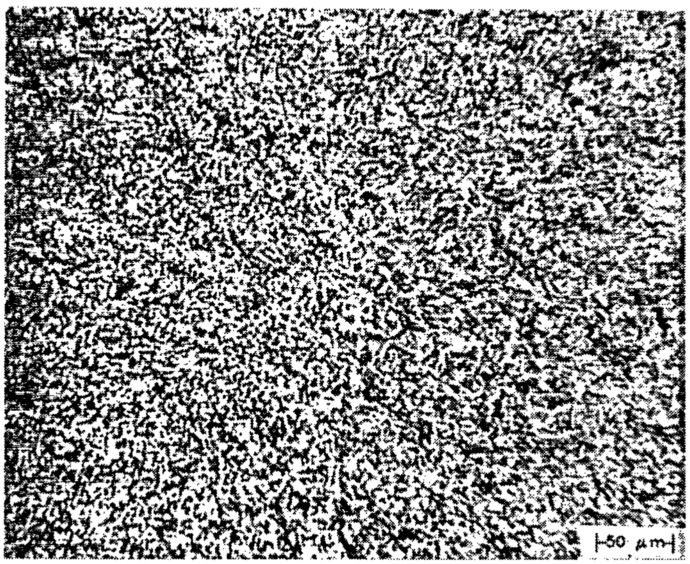
Figure 4: Photomicrographs of tin.

of theoretical. Analysis of the distribution and composition of the phases of Kirksite alloys indicates significant improvements in secondary phase dispersion compared with cast material due to rapid solidification. Figure 5a shows a photomicrograph of cast, equilibrium-cooled Zn-Al-Cu alloy. The same alloy spray formed at 52 kg/h (115 lb/h) is shown in Figure 5b. Figure 5c is a photomicrograph of the alloy spray formed at 470 kg/h (1033 lb/h). Vickers hardness values of the spray-formed alloy typically average 140, depending upon density and operating parameters, but have been as high as 165 for some samples. These values compare favorably with the hardness of cast material (~120). Oxides were not detected within the shells during EDS analysis.

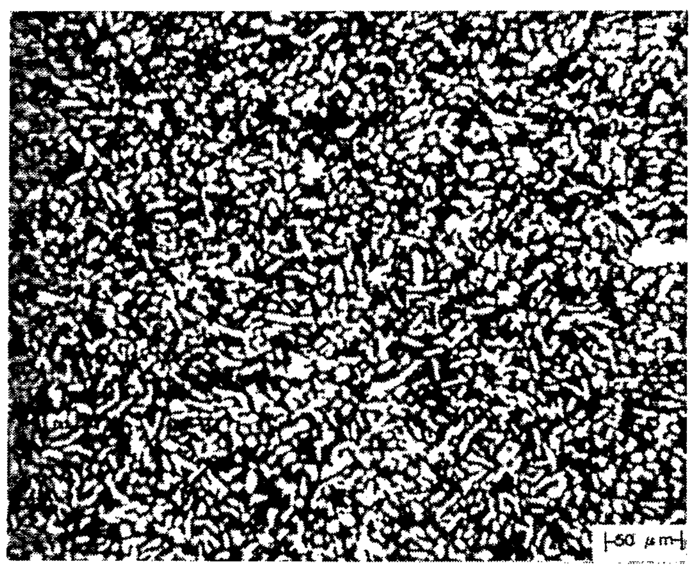
SEM analysis of overspray powder revealed that nearly all particles are spherical. Size analysis was performed using a laser aerosol spectrometer. For both tin and Kirksite, at throughputs of 7 kg/h (15 lb/h), approximately 90% of the powder was less than 10 μm in diameter. For tin, the mean diameter, mass median diameter, Sauter (or area) mean diameter, volume mean diameter, and geometric standard deviation were found to be 7 μm, 22 μm, 18 μm, 45 μm, and 2.4, respectively. For the Kirksite alloy these values were nearly identical (7 μm, 22 μm, 18 μm, 44 μm and 2.6, respectively), despite the higher surface tension and viscosity of the melt. Increasing the metal throughput to 52 kg/h (115 lb/h) while maintaining other spray parameters constant resulted in only a small increase in droplet size and size distribution. The type of atomizing and entrained gas (Ar, N_2, and He) did not have a significant effect on atomization behavior at these relatively low metal throughputs but modelling efforts have indicated that they play a more important role in droplet quench rate and degree of undercooling at higher throughputs.



(a) Cast.



(b) Spray formed at 52 kg/h.



(c) Spray formed at 470 kg/h.

Figure 5: Photomicrographs of etched Zn-Al-Cu alloy.

ACKNOWLEDGMENTS

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