Jorge Mireles[1]
W.M. Keck Center for 3D Innovation,
The University of Texas at El Paso,
El Paso, TX 79902
e-mail: jmireles3@miners.utep.edu

Ho-Chan Kim
Department of Mechanical and
Automotive Engineering,
Andong National University,
Andong, Geyongbuk,
760-759, South Korea
e-mail: hckim@andong.ac.kr

In Hwan Lee
School of Mechanical Engineering,
Chungbuk National University,
Cheongju, Chungbuk,
361-763, South Korea
e-mail: hl1anxoo@gmail.com

David Espalin
e-mail: despalin@miners.utep.edu

Francisco Medina
e-mail: frmedina@utep.edu

Eric MacDonald
e-mail: emac@utep.edu

Ryan Wicker
e-mail: rwicker@utep.edu

W.M. Keck Center for 3D Innovation,
The University of Texas at El Paso,
El Paso, TX 79902

Development of a Fused Deposition Modeling System for Low Melting Temperature Metal Alloys

This research focused on extending the applications of fused deposition modeling (FDM) by extrusion and deposition of low melting temperature metal alloys to create three-dimensional metal structures and single-layer contacts which may prove useful for electronic interconnects. Six commercially available low melting temperature solder alloys (Bi36Pb32Sn31Ag1, Bi58Sn42, Sn63Pb37, Sn50Pb50, Sn60Bi40, Sn96.5Ag3.5) were tested for the creation of a fused deposition modeling for metals (FDMm) system with special attention given to Sn–Bi solders. An existing FDM 3000 was used and two alloys were successfully extruded through the system's extrusion head. Deposition was achieved through specific modifications to system toolpath commands and a comparison of solders with eutectic and non-eutectic compositions is discussed. The modifications demonstrate the ability to extrude simple single-layer solder lines with varying thicknesses, including sharp 90 deg angles and smooth curved lines and showing the possibility of using this system for printed circuit board applications in which various connections need to be processed. Deposition parameters altered for extrusion and the deposition results of low melting temperature metal alloys are introduced. [DOI: 10.1115/1.4007160]

Introduction

Additive manufacturing (AM) refers to the fabrication of complex, customized parts derived from digital data or computer-aided designs and distinguishes itself from traditional manufacturing methods in that the process (from concept to part) is relatively fast and there is no need for expensive tooling, molds, or dies. FDM, developed and initially commercialized by Stratasys, Inc. in 1990, is an AM technology that utilizes a heated extrusion process to produce accurate polymer prototypes and end-use parts [1,2]. Part fabrication is carried out by an extrusion head traveling in the X and Y directions while depositing a semimolten thermoplastic through a small nozzle (as small as 0.254 mm diameter). Layers are deposited on a build stage that moves a prescribed distance down after the completion of each layer. Temperatures are monitored and controlled for both the materials being deposited and the build chamber. Thermoplastic materials are available and continuously updated by Stratasys for commercial use. Due to the ability to manually adjust build parameters (e.g., extrusion temperatures, material flow rates, extrusion head travel speeds) using earlier FDM systems, research has been conducted on the processing of noncommercial materials, such as polymethylmethacrylate [3], polypropylene [4], and polycaprolactone [5].

Most work involving metals in the field of AM utilize high temperature metals processed with technologies, such as electron-beam melting [6], direct metal laser sintering [7], and laser engineering net shaping (LENS) [8]. Metal-polymer material systems have also been investigated for use with FDM and exhibit similar properties (e.g., stiffness) to FDM polymers while demonstrating other useful properties, such as conductivity [9,10]. This work, however, utilized a polymer binder that required additional postprocessing to achieve dense metal parts, which is not required when utilizing a direct metal alloy approach as is presented in this manuscript. Low melting temperature alloys exhibit advantageous properties, such as wetting, solderability, and low creep rates [11] that are useful in conductive media applications, such as soldering interconnections for circuit boards and for three-dimensional deposition using AM technologies like FDM in which high temperature metal alloys would be inapplicable. Although ideal for use with FDM, low melting temperature alloys may have limited application since they exhibit failure during thermal cycling between the temperatures of 40 °C and 100 °C due to microstructural coarsening that leads to cracking [11]. However, processing low melting temperature metal alloys with AM technologies may help to reduce soldering times for building circuit board prototypes that ultimately reduces time-to-market, cost, and improves quality control.

Through the modifications of extrusion parameters (e.g., extrusion head travel speed and envelope temperature), the fused deposition modeling of solder filaments was accomplished in this work. Commercial solder filaments, including Bi36Pb32Sn31Ag1, Bi58Sn42, Sn63Pb37, Sn50Pb50, Sn60Bi40, and Sn96.5Ag3.5 were utilized in this study to achieve FDMm. Alloys with eutectic

[1]Corresponding author.
Contributed by the Electronic and Photonic Packaging Division of ASME for publication in the Journal of Electronic Packaging. Manuscript received February 28, 2012; final manuscript received June 22, 2012; published online February 26, 2013. Assoc. Editor: Kyoung-sik (Jack) Moon.

and non-eutectic compositions were processed and compared to evaluate the hypothesis that non-eutectic solders are more suited for fused deposition due to their liquid–solid mixture present below their liquidus temperature. Moreover, this solid–liquid mixture may allow for better deposition control as a result of higher viscosities when compared to eutectic alloys. The challenges of adapting a commercial FDM system to process low melting temperature metal alloys are described and solutions for these challenges are presented, including achieving a consistent material flow rate, eliminating material clogging in the extrusion head, specifying deposition speeds, obtaining layer-by-layer deposition, and ensuring continuous deposition results.

Materials and Methods

Material. Six commercial solders were used in this study, including Bi36Pb32Sn31Ag1, Bi58Sn42, Sn63Pb37, Sn50Pb50, Sn60Bi40, and Sn96.5Ag3.5 (AIM, Cranston, RI) of which all had a filament diameter of 1.575 mm (0.062 in.) matching the diameter of commercial FDM materials. Particularly, three eutectic solders (Bi58Sn42, Sn63Pb37, and Sn96.5Ag3.5) and three non-eutectic solders (Bi36Pb32Sn31Ag1, Sn50Pb50, and Sn60Bi40) were used to investigate the melting and deposition behavior of each.

FDMm System. Although newer systems are available, the FDM 3000 (Stratasys, Inc., Eden Prairie, MN) provides the ability to modify the operating temperatures, machine's programming code, and feed rates that pertain to different materials. The extrusion head is the key component in the overall function of the FDM 3000 and entails two liquefiers heated by resistance coils and stepper motors that drive a filament into the liquefier for extrusion through various sized tips. Stock material is fed through a 90 deg bend in the liquefier as portrayed in Fig. 1. The extrusion head moves in accordance to automove control language (ACL) prepared by Insight software (Stratasys Inc., Eden Prairie, MN). All software modifications performed in this study were used to alter the machine ACL code that controls the deposition and traversing speed command of the extrusion head. Figure 2 shows the commands that an FDM 3000 system executes when depositing a material. Steps within this sequence of commands, such as specifying flow rates, predelays, and rollback speed of the stepper motors, are important to modify so that continuous lines can be obtained with solder materials. These modifications are necessary to accommodate the relatively low viscosities of the molten metals when compared to traditional FDM thermoplastic materials. Additionally, the work performed in this study utilized a microdispensing technique to deposit the molten metal and as such is different from traditional FDM, which deposits a semimolten thermoplastic.

Experiment I. Qualitative evaluations for each of the six solders were performed to gauge the consistency of flow within the liquefier. The extrusion nozzle was modified from a diameter of

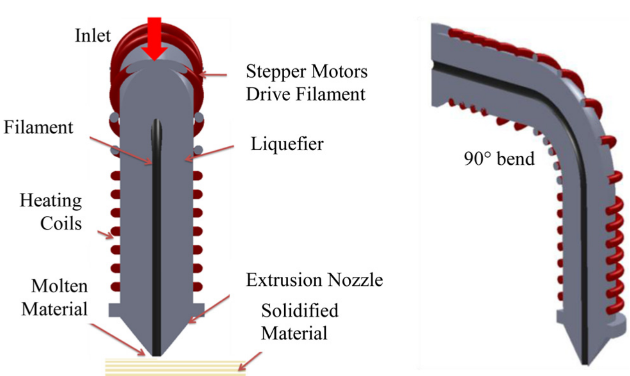

Fig. 1 Schematic of liquefier used for FDM

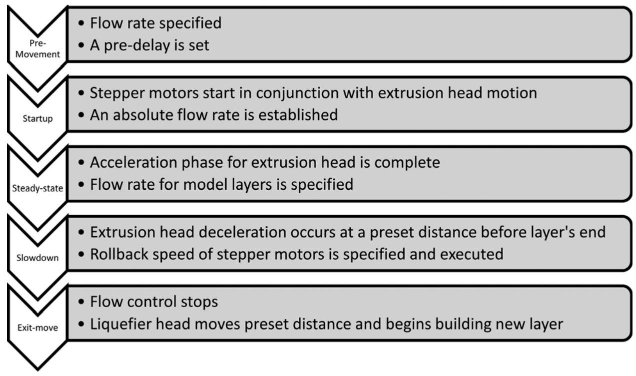

Fig. 2 Execution of main ACL commands

0.406 mm (0.016 in.) to a larger diameter of 1.588 mm (0.0625 in.) to reduce clogging of the extrusion nozzle and eliminate buckling at the liquefier entrance. For these experiments, the extrusion head was held static, the flow rate (rotation speed of motors) was varied from 100% (normal flow) to 600% (maximum flow) using 50% increments, and the liquefier temperature was varied from the corresponding solder melting temperature to 290 °C (maximum system temperature for the liquefier) using 5 °C increments. The FDMm extrusion temperatures for each solder were determined by consulting each solder's phase diagram and selecting a temperature within the solder's molten range. A consistent flow of the solder filament through the liquefier was experimentally determined to mitigate buckling or clogging that can occur when a filament exhibits low stiffness or high viscosity at the liquefier inlet. Also, excess material flow can occur at the outlet if viscosity is too low [12] causing uncontrolled deposition.

Experiment II. Based on the results from experiment I, candidate materials were selected for which extensive deposition experiments were performed. The results were then compared to traditional FDM 3000 thermoplastic materials. The focus of this set of experiments was to determine the deposition parameters that result in continuous roads.

Insight software produces a modifiable machine ACL code that is sent to the FDMm system. A toolpath file containing ACL commands for the FDMm machine controls specific components of the FDMm system throughout extrusion as discussed previously and shown in Fig. 2. The software modifications performed involve changing commands within the ACL code. The premove command uses a wait command to allow the FDM polymer to commence depositing slightly before the tooling head traverses. This wait period (0.08 s for FDM polymer materials) ensures that deposited roads are continuous throughout. Using solders with FDMm results in more rapid flow of material through the nozzle. To mitigate excess material accumulation at the start of a road, this wait time was reduced to 0.01 s based on experimentation of the start and stop results of various samples. A step rate command that defines the extrusion head velocity, typically 1000 microsteps/second (1 in./s) for polymer materials, was reduced to 100 microsteps/second (0.10 in./s) to account for the discontinuous lines that were produced by microdispensing and relatively lower viscosities of the solders when compared to the conventional FDM polymer materials. There is a proportional dependence between the stepper motor speeds and the extrusion head velocity. The material flow rate can be adjusted by modifying (1) the step rate command within the ACL code, (2) a midmove command within the ACL code, and (3) the front panel controls. To retain the same material flow rate while reducing the extrusion head velocity (the system automatically reduces material flow rate with the corresponding reduction in head velocity), the material feed motor speed was increased up to a maximum of 50% via a midmove command within the ACL code and the flow was increased to 450% above the standard machine flow using the front panel controls of the system. These changes essentially increase the deposition rate to produce continuous lines.

Results and Discussions

Experiment I Results. The eutectic composition for multicomponent material systems typically represents the lowest solidification temperature for these material systems, and the solidification temperature is an important parameter when using FDM technology because it dictates the lower limit of the extrusion temperature. Material composition is a major factor since presence of certain metal components can create coarsening or agglomeration within the liquefier that can cause clogging of the nozzle [13]. All solder materials that were tested required a higher extrusion temperature when compared to the corresponding melting temperature (Table 1). These relatively high extrusion temperatures were employed to circumvent friction caused by the 90 deg bend in the liquefier as well as ensuring high enough temperatures to overcome the temperature differential in the liquefier, which is caused by conductive heat loss [12]. Temperature measurements acquired with type K thermocouples indicated an approximate 65 °C temperature difference between the liquefier temperature and the extrusion nozzle exit when processing acrylonitrile-butadiene-styrene (ABS) with the default processing parameters. This temperature difference or thermal energy loss illustrates the need for processing the FDM material at temperatures above the melting temperature. The relatively high liquefier temperatures are required to (1) compensate for the energy lost during the flow of material, and (2) supply energy at a high enough rate, so that the material is melted within the liquefier's length. Table 1 presents the results of utilizing elevated temperature and provides qualitative results demonstrating the candidate materials Bi58Sn42 and Sn60Bi40. Note that the Bi58Sn42 was processed 82 °C above its melting point and Sn60Bi40 was processed 92 °C above the lower limit of its melting temperature range. The Sn60Bi40 required processing at a relatively higher temperature possibly because of the increased tin content (18% more tin than the eutectic composition). Attempting at extruding below these temperatures resulted in clogging of the nozzle. The same approach of using relatively high extrusion temperatures is also employed for commercial FDM polymer materials as evident with ABS in which the FDM extrusion temperature is 270 °C, yet the typical melting temperature when using screw extrusion is 200 °C [14].

Central to the FDM process is the ability to extrude a wide range of thermoplastics from which amorphous materials are favorable because of a viscous paste formation that retains its extruded shape as opposed to crystalline polymers which exhibit lower viscosities when melted [15]. Similar to amorphous versus crystalline materials is the behavior observed between eutectic and non-eutectic metal alloys. Since non-eutectic metal alloys exhibit higher viscosities due to a solid–liquid mixture state[16], it is hypothesized that non-eutectic metal alloys are more suited for extrusion in FDM and have a better opportunity to maintain the shape of the filament during extrusion as is the case with amorphous polymers in traditional FDM.

The results for the Sn-Pb solders rendered inconsistent deposition (i.e., flow of solder stopped throughout deposition) when varying the flow rate as well as the extrusion temperature from 185 °C to 290 °C, and therefore limited experimentation was conducted for these solders. Similar problems have been observed in other work [17,18], including the coarsening of the Sn-Pb solder when maintained at elevated temperatures for prolonged periods which can cause nozzle clogging [19]. During deposition, both eutectic and non-eutectic Sn-Ag solders clogged the liquefier which may have been due to successive heating and cooling of the machine when turned on and off causing the effect of solid phase separation that creates Ag3Sn agglomerates exhibiting a higher melting temperature than the original alloy [20]. Such effects causing higher temperature agglomerates may not be as prevalent in other alloys since metals, such as Ag (961 °C (1762 °F)), or metals with melting points outside the system's temperature capabilities, are not present. Assuming agglomeration was the origin, resolving this clogging as well as inconsistent deposition would require using a higher temperature (above system maximum temperature) to further melt the agglomerates that result from the solder cooling within the liquefier. Moreover, using a system with higher temperature capabilities to process solders whose liquidus range is relatively high (>200 °C) would potentially help mitigate additional mechanisms that caused clogging, such as (1) friction created within the liquefier, (2) temperature differential from one point of the liquefier to another, and (3) conductive heat loss from the resistance heater to the filament within the liquefier. Finally, non-eutectic Sn60Bi40 and eutectic Bi58Sn42 solders were tested, and these material systems demonstrated the most consistent deposition results for all of the material systems tested. Both Sn60Bi40 and Bi58Sn42 did not pose any clogging issues throughout deposition. From observations, the difference between non-eutectic Sn60Bi40 and eutectic Bi58Sn42 was in the behavior during deposition—the non-eutectic solder retained its as-deposited shape more consistently than its eutectic counterpart.

Experiment II Results. Defining solder flow was challenging due to the complex behavior occurring throughout the liquefier which may be attributed to slip between the liquefier walls and the melt flow, slip between feed-rollers and filament, uneven distribution of heat flux due to arbitrary distribution of heating coils, phase changes, and stiction effects as the material is driven into the liquefier [21,22]. Based on the results from experiment I, Bi58Sn42 and Sn60Bi40 were further investigated to determine their deposition behavior as layered structures were fabricated. It was observed that these solder materials did not start flowing immediately after driving the materials into the liquefier. In addition, when the solid solder was no longer being fed into the liquefier, solder material within the liquefier continued to flow. This deposition behavior warranted the software modification previously discussed. Simple measurements were taken to compare line dimensions of the deposited Sn–Bi solders and an ABS polymer. Table 2 presents the properties gathered from manufacturer data for each material and the results for the dimensions of ten lines fabricated with FDMm. When compared to eutectic Bi58Sn42, non-eutectic Sn60Bi40 produced better deposition results as determined by smaller mean line widths and smaller standard deviation of the line widths due to the relatively higher viscosity that is

Table 1 Material's melting temperatures and experiment I results

Composition	Solder type	Melting temperatures	Qualitative results
Eutectic	Bi58Sn42	138 °C (280 °F)	Deposited consistently
	Sn63Pb37	182 °C (360 °F)	Inconsistent deposition, inlet buckling
	Sn96.5Ag3.5	221 °C (430 °F)	Clogged deposition head
Non-eutetic	Sn60Bi40	138 °C–170 °C (280–338 °F)	Deposited consistently
	Sn50Pb50	183–212 °C (361–414 °F)	Inconsistent deposition, inlet buckling
	Bi36Pb32Sn31Ag1	95–136 °C (203–277 °F)	Clogged deposition head

Table 2 Comparison of 10 layers each of Sn–Bi or ABS

	Bi58Sn42	Sn60Bi40	ABS
Z thickness, $\mu \pm \sigma$ (mm (in.))	1.85 ± 0.396 (0.073 ± 0.016)[a]	1.69 ± 0.145 (0.067 ± 0.006)[a]	0.254 (0.010)[b]
Road width, $\mu \pm \sigma$ (mm (in.))	1.67 ± 0.442 (0.066 ± 0.017)[a]	1.56 ± 0.172 (0.061 ± 0.007)[a]	0.76 (0.030)[b]
System temperature (°C)	220 °C(428 °F)[a]	230 °C(446 °F)[a]	270 °C(518 °F)[b]
Tensile strength (MPa)	51.7[c]	52.5[c]	22[c]
Elongation at break (%)	35[c]	35[c]	6[c]

[a]According to deposition results.
[b]According to system specifications, standard deviation not available.
[c]According to manufacturer information.

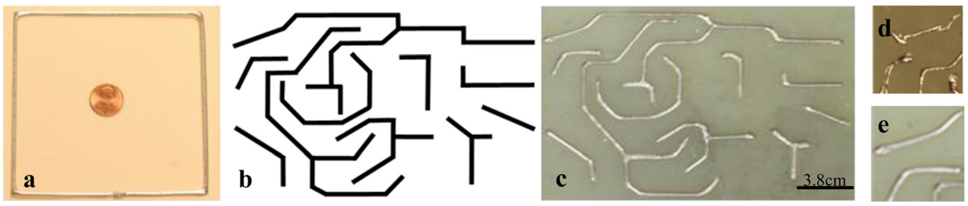

Fig. 3 Two-dimensional deposition (*a*) fused deposition of non-eutectic Sn–Bi solder lines, (*b*) design of circuit pattern, (*c*) fused deposition of non-eutectic Sn–Bi circuit pattern, (*d*) pattern built using eutectic Sn–Bi, and (*e*) pattern built using non-eutectic Sn–Bi

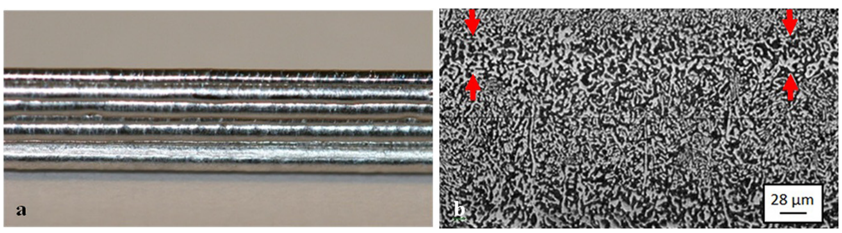

Fig. 4 Multilayer deposition of Sn–Bi (*a*) multilayer line and (*b*) 360× optical image of stacked layers that were polished and etched (interface is highlighted with arrows)

attributed to a solid phase present within the liquid at temperatures above the solidus and below the liquidus [19].

Deposition Results and Capabilities. After initial deposition trials, toolpaths were generated to produce lines with cornered features. Figure 3 presents the production of lines made of Sn–Bi solder, which includes different length lines and sharp 90 deg turns. As shown, the lines produced in Figs. 3(*a*) and 3(*c*) are continuous and reproducible as observed through repeated experimentation. Figure 3(*c*) shows a circuit pattern produced by FDMm using non-eutectic Sn–Bi solder (see the prescribed circuit pattern shown in Fig. 3(*b*)). Figures 3(*d*) and 3(*e*) compare the build patterns using eutectic and non-eutectic materials, respectively. Note that by using the non-eutectic material, more continuous lines with more consistent thicknesses were produced (Figs. 3(*c*) and 3(*e*)) and did not leave excess trails of material at the completion of a path as was observed with the eutectic Sn–Bi solder (Fig. 3(*d*)).

Central to the advantages of AM technologies is the rapid production of three-dimensional components. Therefore, one goal of this project was to achieve multilayer deposition, wherein one line of solder was deposited, the build platform was moved downward a distance in the z-direction, and another line was deposited over the previous line. Figure 4 depicts a close-up view at the stacking of a multilayer Sn–Bi component. Figure 4(*b*) shows the mixed phases of Bi58Sn42 (dark regions are Sn-rich phase and light regions are Bi-rich phase) and depicts the interface from one layer to another (magnified at 360×) taken by a Leica MEF4M optical digital imaging system. The stacked layers were mounted in an epoxy, polished and etched with a 2% Nital solution for 15 s. The results in Fig. 4 show there appears to be a consistent bond between layers, and the microstructure depicts a continuous interface between layers. The successful layer-by-layer stacking capabilities demonstrated potential for producing three-dimensional components with complex geometries using the FDMm system.

Conclusions

FDM systems have been used for over two decades to create prototypes and end-use models made of thermoplastics, such as ABS. This research explored the extended use of FDM to include metal alloys with low melting temperatures. The results suggest the driving factors in successfully depositing metal alloys using FDM are melting temperature and phase transition characteristics according to alloy composition. Low temperature alloys in the range of 100 °C–150 °C with a composition of Sn–Bi deposited continuous metal lines, and non-eutectic Sn–Bi demonstrated improved control of deposition as measured with line widths when compared to eutectic Sn–Bi. Solder composition appears to determine the ability for a metal alloy to be successfully extruded using FDM as both eutectic and non-eutectic Sn-Pb and Sn-Ag solders could not be successfully used. Possible issues for extrusion include coarsening effects for the Sn-Pb solder and agglomeration effects for the Sn-Ag solder. A non-eutectic alloy (Bi36Pb32Sn31Ag1) with a melting temperature range of 95 °C–136 °C (203 °F–277 °F) was expected to deposit well; however, it is believed that segregation from the liquid/solid phase in

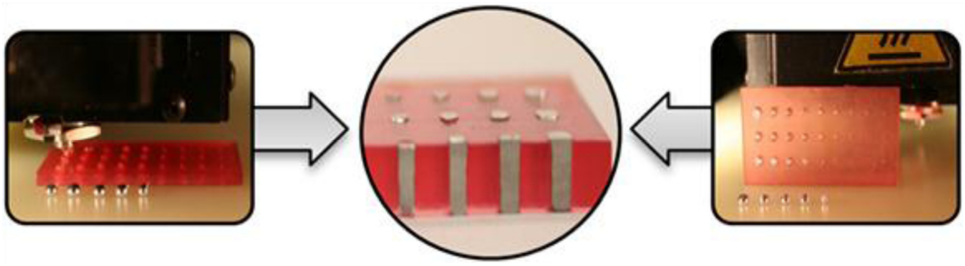

Fig. 5 Deposition of Sn–Bi via FDMm into 3D vias

Sn-Ag solders due to prolonged cooling from switching the system on and off caused agglomeration which clogged the head and did not allow for proper deposition. The Sn-Pb solders also did not perform well during deposition due to clogging of the liquefier. Sn–Bi alloys were used extensively throughout this research and performed the best when compared to the other solders due to their composition and relatively low melting temperatures (with the non-eutectic Sn–Bi composition performing the best overall). This project demonstrated the ability of FDM to deposit metal alloys both in two-dimension and three-dimension. Applications may include fabrication of tooling, structural components, as well as traces made of conductive media.

Future Work

Further work with FDMm and conductive media is suggested to create electronic interconnections and filling vias in traditional and three-dimensional electronic components. As shown in Fig. 5, the FDMm can effectively extrude Sn–Bi conductive solder into varying spaces to be used as a bridge between two electronic components in a circuit board. Work needs to be done in this area to further test the reliability and reproducibility of working solder contacts. Successful work performed in this area can aid in the development of efficiently packaged electronics through the use of AM technologies.

Results described in this paper show that there is still much to be done in optimizing an FDMm system. As observed in this research, there was great difference in deposition capabilities from one material to another (SnBi alloys produced the most consistent deposition results). There is a vast variety of solder materials to choose from which may be candidates for FDMm, such as Sn52In48, Bi58Pb42, Bi67In33, In97Ag3, and many others with melting temperatures below 142 °C (290 °F), or melting temperatures well under the maximum temperature capabilities for an FDM 3000 system. Future work may include an expansion of material to not only solder alloys but also high-strength metal alloys that could prove to be useful for rapid manufacturing applications that require high-strength characteristics. Based on the deposition experiments, there were major differences in start and stop deposition characteristics from one solder to another. For future work, an extrusion method, such as the one used by modern FDM systems (e.g., Fortus 900mc and Fortus 400mc), may be employed in which a single straight short nozzle and a liquefier with a focused high temperature heating point are utilized, which would reduce friction effects and provide more control over flow behavior during deposition.

Acknowledgment

The research described in this paper was performed within the W.M. Keck Center for 3D Innovation at the University of Texas at El Paso (UTEP). Primary support for the research was provided through research Contract No. N000140710633 from the Office of Naval Research. Additional support was provided by the UTEP Louise Stokes Alliance for Minority Participation program funded through Grant No. HRD-0703584 from the National Science Foundation, and the Basic Science Research Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2010-0013209). The authors are grateful for the collaborative support that was provided by Dr. Brent Stucker from the University of Louisville. Mr. David Rodriguez also participated in various ways throughout the project for which the authors are grateful. The findings and opinions presented in this paper are those of the authors and do not necessarily reflect those of the sponsors of this research.

References

[1] Chua, C. K., Leong, K. F., and Lim, C. S., 2003, *Rapid Prototyping: Principles and Applications*, World Scientific Publishing Co., Singapore.

[2] Wohlers, T., 2005, "New Trends and Development in Additive Fabrication," *Virual Modeling and Rapid Manufacturing*, P. J. Bartolo, ed., Taylor & Francis/Balkema, The Netherlands, pp. 3–5.

[3] Espalin, D., Arcaute, K., Rodriguez, D., Medina, F., Posner, M., and Wicker, R., 2010, "Fused Deposition Modeling of Patient-Specific Polymethylmethacrylate Implants," Rapid Prototyping J., **16**(3), pp. 164–173.

[4] Kalita, S. J., Bose, S., Hosick, H. L., and Bandyopadhyay, A., 2003, "Development of Controlled Porosity Polymer-Ceramic Composite Scaffolds via Fused Deposition Modeling," Mater. Sci. Eng., C, **23**(5), pp. 611–620.

[5] Cao, T., Ho, K. H., and Teoh, S. H., 2003, "Scaffold Design and In Vitro Study of Osteochondralcocultrue in a Three-Dimensional Porous Polycarprolactone Scaffold Fabricated by Fused Deposition Modeling," Tissue Eng., **9**(1), pp. 103–112.

[6] Gaytan, S. M., Murr, L. E., Medina, F., Martinez, E., Lopez, M. I., and Wicker, R. B., 2009, "Advanced Metal Powder Based Manufacturing of Complex Components by Electron Beam Melting," Mater. Technol.: Adv. Perform. Mater., **24**(3), pp. 180–190.

[7] Khaing, M. W., Fuh, J. Y. H., and Lu, L., 2001, "Direct Metal Laser Sintering for Rapid Tooling: Processing and Characterization of EOS Parts," J. Mater. Process. Technol., **113**, pp. 269–272.

[8] Atwood, C., Ensz, M., Greene, D., Griffith, M., Harwell, L., Reckaway, D., Romero, T., Schlienger, E., and Smugeresky, J., 1998, *Laser Engineered Net Shaping (LENS): A Tool for Direct Fabrication of Metal Parts*, Laser Institute of America, Albuquerque, NM, pp. 1–7.

[9] Agarwala, M. K., Weeren, R. V., Bandyopadhyay, A., Whalen, P. J., Safari, A., and Danforth, S. C., 1996, "Fused Deposition of Ceramics and Metals: An Overview," Proceedings of the Solid Freeform Fabrication Symposium, Austin, Texas.

[10] Masood, S., and Song, W. Q., 2004, "Development of New Metal/Polymer Materials for Rapid Tooling Using Fused Deposition Modeling," Mater. Des., **25**(7), pp. 587–594.

[11] Mei, Z., Holder, H. A., and Vanderplas, H. A., 1996, "Low-Temperature Solders," Hewlett-Packard J., **10**, pp. 91–98, available at http://www.hpl.hp.com/hpjournal/96aug/aug96a10.pdf

[12] Bellini, A., and Bertoldi, M., 2004, "Liquefier Dynamics in Fused Deposition Modeling," ASME J. Manuf. Sci. Eng., **126**, pp. 237–246.

[13] Kraft, T., Rettenmayr M., and Exner, H. E., 1996, "An Extended Numerical Procedure for Predicting Microstrucuture and Microsegregation of Multicomponent Alloys," Modell. Simul. Mater. Sci., **4**(161), pp. 161–177.

[14] Karahaliou, E. K., and Tarantili, P. A., 2009, "Preparation of Poly(acrylonitrile-butadiene-styrene)/Montmorillonitenanocomposites and Degradation During Extrusion Reprocessing," J. Appl. Polym. Sci., **113**(4), pp. 2271–2281.

[15] Giles, H. F., Wagner, J. R., and Mount, E. M., 2005, *Extrusion: The Definitive Processing Guide and Handbook*, William Andrew, Inc., Norwich, NY, pp. 179–184.

[16] Humpston, G., and Jacobson, D. M., 2004, *Principles of Soldering*, ASM International, Materials Park, OH, pp. 19–21.

[17] Dreyer, W., and Muller, W. H., 2000, "A Study of the Coarsening in Tin/Lead Solders," Int. J. Solids Struct., **37**, pp. 3841–3871.

[18] Kang, S. K., Rai, R. S., and Purushothaman, S., 1996, "Interfacial Reactions During Soldering With Lead-Tin Eutectic and Lead (Pb)-Free, Tin-Rich Solders," J. Electron. Mater., **25**(7), pp.1113–1120.

[19] Finke, S., and Feenstra, F. K., 2002, "Solid Freeform Fabrication by Extrusion and Deposition of Semi-Solid Alloys," J. Mater. Sci., **37**, pp. 3101–3106.
[20] Shen, J., Liu, Y. C., Gao, H. X., Wei, C., and Yang, Y. Q., 2005, "Formation of Bulk Ag_3Sn Intermetallic Compounds in Sn-Ag Lead-Free Solders in Solidification," J. Electron. Mater., **34**(12), pp. 1591–1597.
[21] Bellini, A., 2002, "Fused Deposition of Ceramics: A Comprehensive Experimental, Analytical and Computational Study of Material Behavior, Fabrication Process and Equipment Design," Ph.D. thesis, Drexel University, Philadelphia, USA.
[22] Yardmci, A., 1999, "Process Analysis and Development for Fused Deposition," Ph.D. thesis, University of Illinois at Chicago, Chicago.