

Liquid Metal Jetting for Printing Metal Parts

John W. Priest
The University of Texas at Arlington
Box 19017
Arlington, TX 76019

Charles Smith
The University of Texas at Arlington
Electrical Engineering
Box 19016
Arlington, TX 76019

Patrick DuBois
Automation & Robotics Research Institute
Box 19045
7300 Jack Newell Blvd.
South Ft. Worth, TX 76118

ABSTRACT

Liquid Metal Jetting (LMJ) is solid freeform fabrication process for producing metal mechanical parts and electronic interconnects. It is a technology similar to ink jet printing where individual molten droplets are accurately printed. LMJ will produce metal parts on demand from a CAD database with functional performance parameters similar to metal parts produced by machining or casting. By controlling solidification rates and metal alloy composition, LMJ is able to produce parts with unique properties such as metal matrices and functionally graded materials. This paper will review the current status of LMJ and future applications for this technology.

One emerging manufacturing technology that addresses many challenges in solid freeform fabrication (SFF) is liquid metal jet printing (LMJP). The process is based on technology analogous to ink-jet printing. This agile additive method dispenses individually controlled microballs of molten metals to precise locations. Unlike spray forming and spray deposition process which spray materials in an uncontrolled manner, LMJP dispenses and controls every "single molten droplet" of material to a specific location using digitally stored computer-aided design (CAD) data in a highly reproducible manner. The direct-write, additive nature of an LMJP system offers an agile approach. Potential applications for LMJP include the ability to rapidly fabricate 3-d mechanical parts and electronic circuitry. This paper discusses research issues in the development of liquid metal jet printing systems. The technical issues that affect jet operation and the quality of jetted materials are also discussed.

Background of Jetting Research

The Frenchman Nollet wrote in 1754 of observations made on a low-speed stream issuing from a small diameter nozzle [1]. He commented on the formation of drops, and the ability of a charged rod to deflect them. Lord Raleigh undertook the first thorough and accurate mathematical analysis of liquid jets in the 1870s [2,3]. Rayleigh's theoretical work explained the droplet disintegration mechanism as driven by surface tension induced instabilities. Basset [4] published a theory confirming the role of surface tension induced instabilities and the stabilizing effect of viscosity. Experimentalist A. Haenlein built a system to produce very long (up to 5 meter) water-, glycerin- and gasoline-air jets under positive pressures and no external oscillation in 1931 [5]. Weber [6,7], used the data and observations of Haenlein to generate the first cogent and useful analysis of a viscous cylindrical jet with both symmetric and transverse aerodynamic wave actions although the experimental results did not completely agree with the theory.

Electro-mechanical forced stimulation, was studied by Hansell [8] in the 1950's. This greatly broadened the application for jetting. Jet applications changed from fuel injection to rocket propulsion to ink-jet printing. Lee and Spencer [9] used fuel injection mechanisms with fairly broad nozzle length to diameter ratios in the generation of high speed photographic studies of liquid jets. McCormack et. al. [10] in 1965 described the essential elements of a modern forced oscillation experimental water jet system employing a vibrating PZT ceramic crystal

Jetting for building mechanical structures and parts, which is often called solid freeform fabrication (SFF), started with the use of wax and wax like materials. For example, a patent by Mitchell [11] discloses the generation of an object with liquid wax or similar type material using a jet printer. A later patent of Sanders Prototype shows a desktop jetting machine for generating wax parts. These systems used piezoelectric crystals which limited the systems to low melting point temperature waxes. Considerable research on solidification issues in jetting wax was performed by Gao and Sonin[12]. The jetting of molten metals became the natural next step for mechanical and electronic structures.

The field of liquid metal jet printing started in electronics with low temperature solder applications on a suggestion by IBM in 1972 [13]. Work during the 1980s by Heiber in solder jetting resulted in the first LMJP patent for Philips North American in 1989 [14]. The described drop on demand method utilized a lead zirconium titanate piezo-electric (PZT) crystal to generate

a pressure wave for controlled the droplet generation. Since PZT undergoes a phase change and loses its piezoelectricity at a finite temperature (i.e. Curie temperature), the technology described by the Heiber patent was initially useful up to approximately 200°C which limited the technique to very low melting point metals such as low temperature solder. As improved designs and PZT materials with higher operating temperatures became available, medium melting point metals such as 63/37 solder could be jetted.

Several research groups in the late 1980's and early 1990's such as Priest, Smith and DuBois at ARRI/UTA [15-21], Hayes and Wallace at MicroFab Technologies [22-25], and IBM [26] focused on solder jetting research to be used in electronic applications.

Rather than using a piezoelectric crystal to generate droplets, Ted Smith and Winstead at IBM took a different path and in 1993 filed for a patent on a electrodynamic pump for dispensing molten solder [34]. This pump uses a programmable current source with a magnetic coil to produce the jetting force. The pump has been shown to be reliable but is slower than piezoelectric crystal methods.

Several researchers in the early 1990's became interested in using liquid metal jetting to fabricate spherical balls (i.e. powder). Liquid metal jetting is an excellent method for ball generation. These spherical balls (i.e. powder) can be used in solder paste and powder metallurgy. Solder jetting has been reported to produce balls with 5% repeatability in volume. In a 1992 US patent filing, Chun and Passow proposes to charge the droplets to maintain their uniform size [27]. Filed in 1993, Hayes proposes a method for making solder compositions [23].

The benefits of using metal jet printing to directly fabricate 3-d metal parts and structures was obvious. During the early 1990's, research in liquid metal jet printing for manufacturing mechanical structures began. LMJP could produce metal parts on demand directly from a CAD database with functional performance parameters similar to or better than metal parts produced by machining or casting. By controlling solidification rates and metal alloy composition, LMJP can also produce 3 dimensional parts with unique properties such as metal matrices and functionally graded materials. The key material parameters affecting a materials ability to be jetted are the relationship between surface tension and viscosity. Analyses developed by Smith [28,29] and performed at The Automation & Robotics Research Institute at The University of Texas at Arlington have indicated that most molten metals can be jetted. Metals that have been jetted include copper, aluminum, tin, 63/37 solder, low melting point temperature solders, and mercury. In addition to Priest, Smith, and DuBois at ARRI/UTA, other groups led by Chun et.al. at MIT [30] and Orme at University of California at Irvine [31] are pursuing metal jet printing for building mechanical parts and producing uniformly sized metal balls. Chun and Passow developed a method called uniform spray deposition where the metal is jetted but individual droplets are not controlled (i.e. sprayed). In filings starting in 1990, Orme and Muntz has received a series of US patents on an apparatus for droplet stream manufacturing where the meta droplets are printed onto a collector of the shape of the desired product [32].

In addition to working on electronics and mechanical structure applications, several research groups started to examine methods for jetting higher melting point metals. Work done by Smith, Priest and DuBois at ARRI/UTA, IBM and Chun at MIT have resulted in several ideas

and US patents for jetting high melting point temperature metals such as Al, Cu, etc. [33,27]. In the patent filing, Chun suggested locating the lead metaniobate piezoelectric which is connected to a shaft and disk that extends to the molten metal. This keeps the crystal away from the heat.

In 1994, DARPA funded Texas Instruments and UTA/ARRI to build a prototype machine to jet high melting points metals such as copper, for a direct circuit write, environmentally friendly method for printed circuit boards.

The ARRI/UTA group worked on innovative methods for replacing the piezoelectric crystal with heat resistant methods for generating the force to produce droplets. Filed in 1993, the Smith, Priest, and DuBois patent [33] illustrated several innovative apparatus and methods for dispensing high temperature materials.

Liquid Metal Jet Printing System

There are two basic jetting methods: continuous and drop on demand. Continuous jetting is where the material is continuously jetted. Common applications for continuous jetting is high speed printing of patterns on bank checks, date labeling of products, and paper towels with printed designs. A thin liquid jet is considered to be continuous if the break up of the jet and resulting formation of droplets occurs a measurable distance down the jet away from the orifice from which the jet emanates. Such a continuous jet can be caused to breakup in a controlled way which is both uniform and periodic or random aperiodic as in the case of the natural break up of a viscous jet such as pouring syrup. A thin liquid jet is considered to be discontinuous if the break up of the jet and resulting formation of droplets occurs at the nozzle or orifice from which the jet emanates. Such a discontinuous jet is usually denoted as a 'drop on demand' jet and depending upon the exciting mechanism could be either periodic or aperiodic. A major difficulty in identification occurs when the discontinuous jet (i.e., drop on demand jet) is continuously excited in a periodic manner. The resulting drop on demand droplet stream appears identical to the droplet stream formed from a periodically excited continuous jet. A common application for this method is an ink jet printer for personal computers. The advantages of the continuous method is the faster droplet rates (10-100 KHz) and that less energy force is required to produce the droplets. The advantage of drop on demand is that there are no unused droplets. Table that shows the differences and for what applications?

Parameter	Drop on Demand	Continuous
Jet Speed (droplets per second)	less than 10 KHz	10 to 100 KHz in a cylindrical configuration and 5 to 20 KHz in a pump configuration
Droplet Size Relative to Orifice Size (diameter to diameter)	Same which is better for producing smaller drops	Droplet is 1.8 times larger than the orifice diameter which is better for producing larger drops.
Material Usage	Less	Must gutter unwanted droplets. This unused material can be reused in many applications
Generator Force/Energy Required	More	Less

The system for this discussion is a high speed, continuous metal jet printing system. The prototype system, shown in Figure 1, is divided into three distinct areas; 1) supply and head, 2) electrostatic charging and deflection area, and 3) target surface. The metal supply is melted in a pressurized container and the molten metal is forced through the tubing to the jet head. The droplet generator, which is housed in the jet head assembly, applies a pulsing mechanical force on the jet stream to stabilize the droplet formation. The liquid metal exits through an orifice attached to the solder jet head. This process results in the formation of a continuous stream of attached and elongated droplets. As a result of the mechanical excitation and surface tension, droplets break off from the molten metal stream. Generally the orifice diameter determines the size of the droplet, however, the droplet size can be changed within certain tolerances by modifying the force applied to the droplet generator.

The vertical shooter head is mounted to an precision X-Y positioning table. Using the a system shown in Figure 2, molten metals are applied in a precision pattern determined by CAD data. A CAD pattern information file is combined with jetting system knowledge base to develop the process commands. These commands include equipment control, environmental chamber control and numerical control (NC) code via a software package. At break up, a predetermined electrical charge is applied to the droplet according to the CAD data and a jet process knowledge base. The charged droplet is then directed to the target surface or to a catcher system by use of electric field deflection plates. A catcher is used to collect the unused droplets. To maintain a molten droplet and minimize oxidation, it is necessary to enclose the jet head and substrate in a heated, inert environment. A thermally controlled environmental chamber is incorporated for this purpose.

Jetted Materials Results

Jetting systems currently operational have produced output in the form of microballs (40 to 125 μm in diameter), bumps on a substrate, individual wetted drops or splats on substrates, circuit lines, micro-diameter wires and three-dimensional cantilevered structures with very high aspect ratios (10:1).

Current Research Applications

On-going research efforts are being performed at the Automation & Robotics Research Institute at the University of Texas at Arlington, MicroFab Technologies, MIT, IBM, MPM, and The University of California at Irvine.

The ARRI/UTA research laboratory is located in Dallas/Ft. Worth and focuses on high temperature, high speed LMJP technology for mechanical 3-d parts, generating balls, and electronic manufacturing processes. Droplet speeds can be as high as 100 KHz although typical rate are in the order of 30 KHz. A LMJP prototype system is now being used to investigate how to deposit various high temperature metals such as aluminum and steel for building mechanical parts, aluminum printed circuit boards, and ball generation.

MicroFab Technologies Inc. is a company in Plano, Texas that has focused on commercializing solder jetting for surface mount technology in the electronics industry. This

research is led by Drs. Don Hayes and David Wallace. The three applications are fine pitch, ball grid arrays, and flip chip. Funding has been provided by the Advanced Technology Program of the US Department of Commerce. A drop on demand jet machine has been developed with Universal Instruments which produces 60 um diameter droplets with rates up to 2 KHz. It uses drop on demand generators which use piezoelectric crystals. Details and photographs can be found on their ISHM paper on the MicroFab web site [25]. Efforts are underway to integrate Microfab's demand mode technology with MPM's metal jet printing machine.

Research at the University of California at Irvine is being led by Dr. Melissa Orme. The research has focused on new forcing techniques which can modify droplet size and patterns, modeling of droplet collisions, and net form materials synthesis (i.e. rapid prototyping of mechanical parts) [32,35].

MIT has two different research groups in the Department of Mechanical Engineering that are working on jetting. One is led by Dr. Jung-Hoon Chun. Research by Chun has focused on modeling the droplet solidification process, generating balls and solid free form fabrication of mechanical parts [27,35,36,37,38]. Their method of producing metal parts is called uniform spray deposition (UDS). The other group is led by Dr. Sonin who has focused on modeling of the solidification process initially using wax materials [12].

Two other companies have been working on solder jet machines. These are IBM and MPM. The work at IBM (Austin) uses their patented pump and has focused on jetting solder for electronics assembly. Both IBM and MPM have produced prototypes for test and evaluation by several major electronics companies.

Summary

Current research has shown that a number of technical issues must be resolved prior to metal jet printing becoming a successful process in SFF. Major technical issues include:

1. process stability and reliability,
2. impact, solidification, and shape control
3. part and circuit performance.

Process Stability and Reliability

Process stability and reliability is a major problem due to the complexity of the jetting process. To date, liquid metal jet machine have not performed to the levels of quality that is required in industry. Key challenges include oxidation, material contamination, and thermal management and droplet generator reliability.

An important aspect of reliable operation of the jet is eliminating material contamination which can lead to clogging or leaching of contaminants into the molten metals. This means that the choice of both the construction materials used in the design and the filtering methods to

remove contaminants in the raw material are important aspects. The presence of particulate matter such as oxides or intermetallic phases can lead to clogging of the jet.

Impact, Solidification, and Shape Control

Investigations are underway by several research groups to study the impact of liquid metal droplets onto rigid substrates and other jetted droplets [30,31]. Material interaction depends on control of the entire jetting process which is a function of jet parameters such as velocity, perturbation wave frequency, and orifice diameter, material parameters such as absolute viscosity, surface tension, fluid density and temperature, and the target parameters such as temperature, surface roughness, and wetting ability. The importance of each of these factors to the process and the extent to which these factors interact are questions that must be answered with careful experimentation.

A major challenge in solid freeform fabrication concerns fabricating part "features". Many features such as slots, overhangs, etc. will require fixturing. Tolerances for surface finish will also be hard to maintain. Reflowing or surface finishing the part after initial fabrication may be required.

Part and circuit performance

Long term performance and reliability testing of fabricated parts is needed. At this time, the operational testing emphasis has been on solder jetting for flip chip bumping and ball grid arrays using machines developed by MicroFab Technologies, IBM, and MPM.

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References

1. Techno-economic Study. 1978. The Business of Ink Jet Printing, The Research Association for the Paper and Board, Printing and Packaging Industries (PIRA).
2. J.W.S. Rayleigh. 1879. "On the Capillary Phenomena of Jets." Proceedings Roy. Soc., vol. xxix, pp. 71-97.
3. J.W.S. Rayleigh. 1892. "On the Instability of Cylindrical Fluid Surfaces." Phil. Mag., vol. 34, no. 207, pp. 177-180.
4. A.B. Basset. 1894. "Waves and Jets in a Viscous Liquid." American Journal of Math, vol. 16, no. 1, pp. 93-110.
5. A. Haenlein. 1933. "Disintegration of a Liquid Jet." NACA Technical Memorandum No. 659.

6. C. Weber. 1931. "Zum zerfall eines flussigkeitsstrahles." *Ztschr f. angew. Math. und Mech.*, vol. 11, no. 2, pp. 136-154.
7. C. Weber. 1948. "On the Breakdown of a Fluid Jet." Ninth Progress Report, Project MX-833 (section II), University of Colorado, Boulder.
8. Hansell. 1950. U.S. Patent 2,512,743.
9. D.W. Lee and R.C. Spencer. 1932. "Photomicrographic Studies of Fuel Sprays." NACA Report No. 454.
10. P.D. McCormack, L. Crane and S. Birch. 1965. "Derivation of Jet Viscosity Modulation Caused by Injector Vibration." *Brit. Journal Appl. Phys.*, vol. 16, pp. 1911-1912.
11. P. H. Mitchell. 1994. "Method and Apparatus for Manufacturing an Article using a Support Structure for Supporting an Article during Manufacture." US Patent 5362427. Assignee:inventor
12. F. Gao and A. A. Sonin. 1994. "Precise Deposition of Molten Microdrops: the Physics of Digital MicroFabrication" *Proceedings of the Royal Society of Physics - London*, vol 444. pp.533-554.
13. IBM, 1972 "Pulse Jet Solder Deposition". IBM Technical Disclosure Bulletin, vol. 14, pp. 2354-2355.
14. H. Hieber. 1989. "Method of Applying Small Drop Shaped Quantities of Metal Solder from a Nozzle to Surfaces to be Weltded and Device for Carrying Out the Method." U.S. Patent 4,828,886. Assignee: US Philips.
15. J.W. Priest, H. Bordett, C. V. Smith, Jr., and P. DuBois. 1993. "Liquid Metal-Jetting: Its Application to SMT." *Journal of Surface Mount Technology*, vol. 6(4): pp. 4-10.
16. J.W. Priest, E. G. Jacobs, C. V. Smith, Jr., and Pat DuBois. 1993. "Liquid Metal-Jet Technology and its Application in Hybrids Microelectronics Manufacturing." *Proceedings of International Symposium on Microelectronics*, Dallas, Tx., pp. 120-125.
17. J.W. Priest, H. Bordett, C. V. Smith, Jr., and P. DuBois. 1993. "Liquid Metal Jetting". *Proceedings of Surface Mount International*, San Jose, CA., vol 1, pp.522-527.
18. J.W. Priest, H. Bordett, C. V. Smith, Jr., and P. DuBois. 1993. "A Process Overview: Dispensing Molten 63/37 Solder Using Liquid-Jet Technology." *Proceedings of Printed Circuit World Convention*, San Francisco, CA. pp. 3-8.
19. E. Jacobs, J.W. Priest, P. DuBois, and C.V. Smith. 1994. "Material Issues in Liquid Metal Jet Printing Technology." *Proceedings of Annual Meeting of the Texas Academy of Science.* Houston, Tx. pp.73-75.
20. J.W. Priest, E. Jacobs, C.E. Smith, et. al. 1994. "Liquid Metal-Jetting Technology: Application Issues for Hybrid Technology", *International Journal of Microcircuits and Eletronic Packaging*, Vol. 15(3), pp. 219-227.
21. J.W. Priest, C. Smith, P. DuBois, et.al. 1997. " Agile Manufacturing Using Liquid Metal Jet Technology", *Proceedings of ICAM'97*, Lafette, Louisiana.
22. D.B. Wallace. 1989. "Automated Electronic Circuit Manufacturing Using Ink-jet Technology", *Transactions of the ASME Journal of electronic Packaging*, vol. 111, no. 2, p. 108-111.
23. D.J. Hayes, et.al. 1993. "Method and Apparatus for Dispensing Spherical-Shaped Quantities of Liquid Solder", US Patent 529016. Assignee: MicroFab Technologies.

24. D.J. Hayes, D.B. Wallace, M.T. Boldman, and R.E. Marusak. 1993. "Picoliter Solder Droplet Dispensing." *International Journal of Microcircuits and Electronic Packaging*, vol. no., pp. 173-180.
25. MicroFab website 1997 "www.metronet.com/~dwallace".
26. IBM. 1994. "Demonstrations at SMTA Conference." San Jose, California, 1994.
27. J. Chun and C. H. Passow. 1993. "Production of Charged Uniformly Sized Metal Droplets", U.S. Patent 5266098.
28. C.V. Smith, Jr. 1974. "Analysis of Droplet Formation in Ink Jet Printers." Unpublished Research, The University of Texas at Arlington.
29. C.V. Smith, Jr. 1976. "Experimental Determination of Ink Fluid Parameter Variation Effect on Droplet Formation in Ink Jet Printing." Unpublished Research, The University of Texas at Arlington.
30. J.-H. Chun. 1997. "Process-Structure Relationships in the Uniform-Droplet Spray Process." *Proceedings of the 1997 NSF Manufacturing and Design Grantees Conference*, pp.327-328.
31. M. Orme, C. Huang. 1997. "Advanced Materials Synthesis and Manufacturing Using Controlled Droplet Deposition" *Proceedings of 1997 NSF Manufacturing and Design Grantees Conference*, pp.377-378, website www.eng.uci.edu/maeadim.
32. M.E. Orme, et.al. 1994. "Method and Apparatus for Droplet Stream Manufacturing", US Patent 5340090 (continuation-in-part and divisions of US Patents 5259593, 55171360 and 5226948).
33. C.E. Smith, J.W. Priest, and P. N. DuBois. 1996. "Heat-Resistant Broad-Bandwidth Liquid Droplet Generators", U.S. Patent 5560543, Assignee: The University of Texas System.
34. T.M. Smith, et. al. 1995. "Electrodynamic Pump for Dispensing Molten Solder", US Patent 5377961. Assignee: IBM
35. M. Orme. 1993. "A Novel Technique of Rapid Solidification Net-Form Material Synthesis". *Journal of Materials Engineering and Performance*, vol 2, pp. 399-405.
36. C.H. Passow, J.H. Chun, & T. Ando. 1993. "Spray Deposition of a Sn-40 wt pct Pb Alloy with Uniform Droplets," *Metall. Trans. A*, vol 24A, pp 1187-1193.
37. C.A. Chen, J.H. Chun, & T. Ando. 1994. "Microstructural Control by Uniform-Droplet Spray Forming," *Advances in Powder Metallurgy and Particulate Materials*, Toronto, Canada, May vol 6, pp. 227-234.
38. Y. Pyongwon, J.H. Chun. and T. Ando. 1996. "Production and Characterization of Mono-Sized Sn-Pb Alloy Balls", *International Journal of Powder Metallurgy*. vol 32 pp. 155.

