

Directly incorporating electronics into conventional rapid prototypes

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ABSTRACT

This paper reports on a technique for directly incorporating complete electronic circuits in conventional FDM rapid prototypes in which the base material is ABS. The method requires the design for the prototypes to include channels for electrical connections, sockets, and the like; something that it is straightforward to achieve. These channels are filled with liquid Wood's metal, which melts at 70 C - much lower than the melting point of ABS. The temperatures and other conditions required for the process are very similar to those already used in the FDM machine; this should make it simple to incorporate the technology into new FDM machines with comparatively uncomplicated changes to current designs. To demonstrate the new technique, it was used to manufacture a small autonomous robot. This too is described and depicted.

Keywords: FDM rapid prototyping, rapid-prototyped electronics, ECME, ABS, Wood's metal.

1. INTRODUCTION

1.1 Rapid prototyping, direct writing, and electronics

The majority of rapid prototyping machines work with thermoplastics [2]. Two common technologies are the one used in this research — fused deposition modelling (FDM) — which typically deposits acrylonitrile butadiene styrene (ABS), and selective laser sintering (SLS) which typically fuses polyamide (nylon). Some SLS systems can also work with alloy powders such as Inconel 625 to produce porous metal parts; with these it is possible to get sintering densities up to 92% of the parent-metal density [7].

However, no current rapid prototyping machines can create objects from both electrical insulators and conductors, and so make an electronic circuit.

Direct writing technology can do this — it uses ink-jet and micro-nozzle technology to print repeatedly in layers to build up three-dimensional parts and patterns. The inks used can be silver-rich, creating conductors, or can be polymers, creating insulators. There are even systems that work with polymer semiconductors that can directly print electronic components such as transistors into circuits [5].

Unfortunately, direct writing is not a very effective technology for making large robust mechanical parts, whereas rapid prototyping is.

It is to the problem of combining advantages from both these technologies that this paper is addressed. We report here on a method for embedding electrical conductors and electronic components in conventional FDM rapid prototypes. This method has the following characteristics:

1. It uses the same temperatures and conditions as the existing FDM rapid prototyping process that it enhances;
2. It can create circuitry (and such things as heat sinks) in three dimensions; and
3. It can create plugs, sockets, and other holders and connectors so that items like batteries and integrated circuits can simply be plugged into the finished components.

2. RAPID PROTOTYPED ELECTRONIC CIRCUITS

2.1 John Sargrove

At a meeting of the British Institution of Radio Engineers in February 1947 John Sargrove presented a revolutionary manufacturing system for electronic devices, which he called ECME (Electronic Circuit-Making Equipment) [6]. This took Bakelite blanks moulded with channels and cavities, and filled these with molten zinc. This created all the connections, resistors, capacitors, and inductances for a complete radio, and did it entirely automatically. At the end of the process, valves were plugged in by hand and a loudspeaker was connected to complete the device. Figure 1 shows the radio and the ECME production machine.

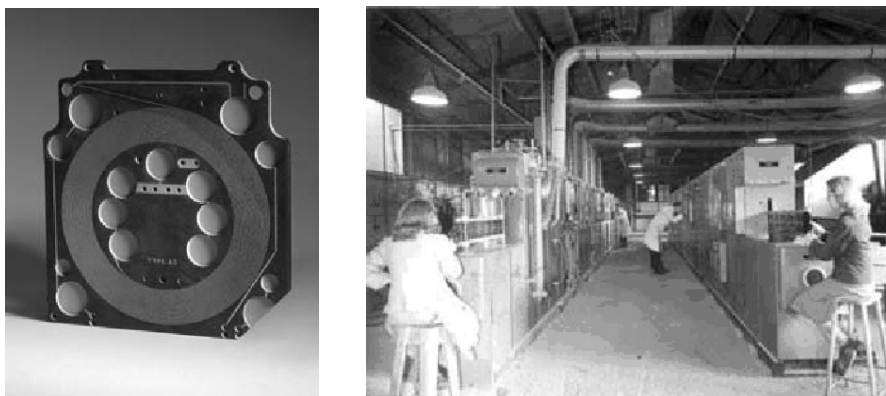


Figure 1: One of the radios automatically made by John Sargrove's ECME machine in the late 1940s, and two of the ECME machines themselves.

Sargrove's work gives a possible way to include electronics in rapid prototypes by using a similar technique, but with an RP-formed polymer component taking the place of the moulded

Bakelite. The rapid prototyping machine used in the research reported in this paper was a Stratasys Dimension FDM machine supplied by Laser Lines Ltd., of Banbury in the U.K. This machine uses ABS as its working polymer.

However ABS is a thermoplastic, whereas Bakelite is a thermoset, and the melting point of zinc is 420° C. ABS and the other thermoplastics used in conventional rapid prototyping melt well below this point, and so parts made from them would be destroyed by molten zinc.

But it is not necessary to use zinc. Wood's metal — an alloy of 50% bismuth, 25% lead, 12.5% tin and 12.5% cadmium — melts at about 70° C. It was decided to use this for the experiments described here, as 70° C is well below the melting point of ABS. The Wood's metal we used was supplied by Lowden Metals Ltd., of Halesowen in the U.K., who market it under the trade name Bend Alloy.

2.2 Syringe-deposited Wood's metal tracks

It was decided to inject the molten Wood's metal into the tracks and cavities using a hypodermic syringe. But initial experiments into this were not encouraging.

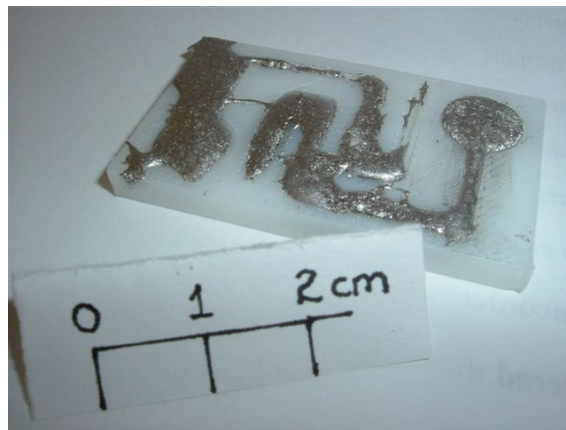


Figure 2: The first result of the syringe experiment.

Figure 2 shows the first results of attempting to inject molten Wood's metal into a channeled test piece. The syringe, the Wood's metal in the Petri dish, and the test part were all pre-heated to a temperature of 90° C. The metal was drawn up into the syringe. The top-left well and channel in Figure 2 were filled with no needle on the syringe; the bottom-right ones were filled with a needle.

The principal difficulty that led to the poor results in Figure 2 was the cooling of both the syringe and (to a lesser extent) the rapid-prototyped part while the metal was being injected. While being deposited, the metal remained molten in the syringe for only 40 seconds or so.

It was decided to put a heating jacket round the syringe. Figure 3 shows the design.

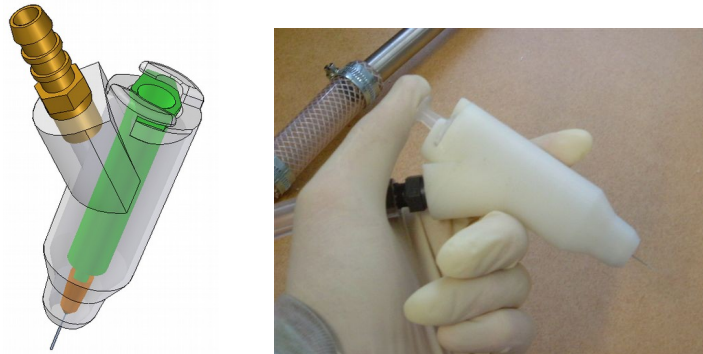


Figure 3: The design for the heating jacket for the syringe (shown in green), and the manufactured jacket in use.

The jacket was made in the rapid prototyping machine that was being used for all the experiments. It was fed with heated compressed air. A low pressure (0.03 bar) was used to prevent the hot air – which escaped around the needle of the syringe – from blowing the molten Wood's metal from the channel in which it was being deposited. A lower voltage on the mains air heater (80V) compensated for this, giving an air temperature around the syringe measured by thermocouple of 90° C. The test part and the Petri dish containing the Wood's metal were placed on the hotplate (again at 90° C). The molten metal was drawn up into the syringe, and then deposited in the channels in the rapid-prototyped test part. Now that everything was maintained at a constant temperature, this process could be done as slowly and as carefully as needed.



Figure 4: Results from the syringe with a heating jacket. The track is 1.2 mm wide.

Figure 4 shows a 1.2mm wide channel filled by this process. The result is even and exhibits excellent electrical continuity. It was found that the very best results were obtained by slightly over-filling the channel, whereupon the surface-tension of the metal caused it to bulge up out

of the channel, and then drawing the excess back into the syringe to bring the level down flush with the ABS surface.

Note that the syringe deposition technique is very similar to the FDM technique already used by the rapid prototyping machine, and that the temperatures employed are also similar to those used in the bulk of the machine and in its deposition head. Therefore it ought to be possible to add this technology to a conventional FDM rapid prototyping machine without radical modification of its design or operating conditions.

2.3 Pits and fences

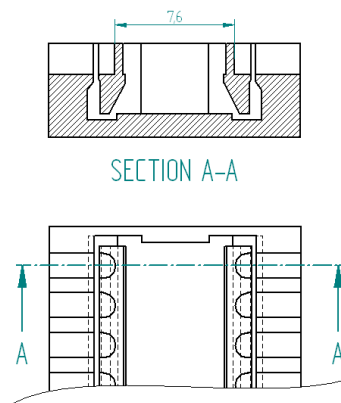
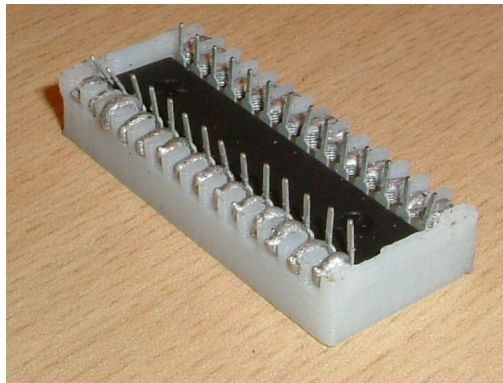


Figure 5: The rapid-prototyped DIL chip holder, and a drawing of its design. Note that the chip is inserted upside-down.

Having achieved a process that worked reliably, we now turned to the design of rapid-prototyped features to accommodate standard electronic components. In particular it was decided to design chip sockets and battery holders, as these would be needed for a robot that we were intending to build using the process to demonstrate it.

Figure 5 shows a DIL chip holder with the chip inserted into it, and a detail of its design. The sectioned central parts, which seem unsupported in that detail, are sacrificial fences that have been added to stop the flow of the molten Wood's metal into the pit designed to accommodate the chip. The fences are, in actual fact, unsupported. This forces the FDM machine to insert weak support material under them to retain them while they are being laid down. The Wood's metal is then injected, and finally the fencing is removed by breaking the weak support material. This exposes a metal face that makes contact with the appropriate chip pin. When the chip is inserted, the metal projects just far enough to bend the pins over-centre, so the chip is pushed further down, locking itself into the pit by the spring-force from its legs. We found that for a standard DIL chip a fence gap of 7.6 mm gave the best chip retention. The pit has a through-hole at the bottom to allow the chip to be ejected by pushing it out with a small screwdriver.

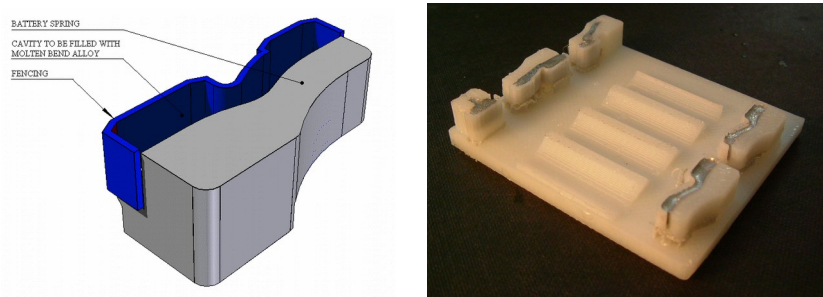


Figure 6: Fencing used to define a battery-holder contact, and the finished battery holder before the fences were removed.

Figure 6 shows a view of the fence structure designed for a sprung battery contact, and a finished battery holder after the Wood's metal had been injected, but before the fencing had been removed.

4. PROVING THE PROCESS BY USING IT TO BUILD A ROBOT

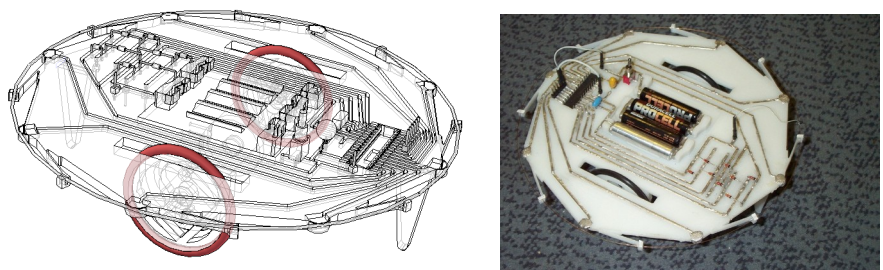


Figure 7: A diagram of the robot made using the techniques described here, and the actual robot working. It is about 200 mm in diameter.

The autonomous robot shown in Figure 7 was built entirely using the techniques described in this paper. It has two motors driving left and right wheels independently. These are controlled by a Microchip PIC 16F73 microcontroller. A wire ring encircling the robot on ABS springs forms a bump sensor. When the robot runs into something the sensor ring touches one of the eight Wood's metal pads round the robot's periphery (made using the fencing technique described above) grounding an input pin on the PIC. The control program in the PIC then causes the robot to back away and head off in the opposite direction. The robot is powered by three AAA batteries.

As a robot, this is not particularly advanced. But that is not the point. It was designed and built to demonstrate that the techniques described in this paper can be used to manufacture complicated electronic and mechanical devices using the extensions to conventional rapid prototyping that we have developed.

5. FUTURE WORK

The next stage of the project described here will be to replace the syringe with a syringe pump (also manufactured using rapid prototyping), and to include thermocouples in the design to allow temperatures, air-flow, and metal-flow rates to be controlled automatically by computer-mediated negative feedback.

Our incorporating electronics into conventional rapid prototypes was the first step in a project to create a self-copying rapid prototyping machine — a machine able to manufacture most of its own component parts. The next stage of this project will be the design, construction, and calibration of servo-controlled movement axes intended for the self-copying rapid prototyping machine. These will be made using the techniques described in this paper.

Finally we are developing material deposition systems for both a polymer and for Wood's metal. The majority of the components of the deposition systems will again be manufactured using the rapid prototyping techniques described here.

Together these will form the self-copying rapid prototyping machine — a real instance of John von Neumann's theoretical *Universal Constructor* [4].

It is not the intention of our self-copying rapid prototyping machine project to profit by restricting any of the intellectual property generated. To be most useful, a self-copying rapid prototyping machine has to be as liberally available as possible. To this end we shall be making all the results public, both by publishing papers such as this, and by releasing all of them — including all CAD designs and documentation — free under the GNU General Public Licence on the Internet [3].

6. CONCLUSIONS

The process we have developed works reliably, and is capable of making real mechatronic devices. As it stands it can be used in conjunction with a conventional FDM rapid prototyper to make such devices, but we intend to combine the two into a single machine.

As the process we have developed uses temperatures and other conditions very close to those already used in existing rapid prototyping machines it should be straightforward to incorporate them into new designs for such machines as well.

REFERENCES

1. Bowyer, A. *The Biology of Rapid Prototyping*, at <http://reprapdoc.voodoo.co.nz/bin/view/Main/BackgroundPage>
2. Chua, C.K. *et al.*: *Rapid Prototyping: Principles and Applications*, World Scientific Publishing, ISBN: 9812381171, 2003.
3. The Free Software Foundation: *The GNU General Public Licence*, <http://www.gnu.org/licenses/licenses.html#GPL>
4. von Neumann, J.: *Theory of Self-Reproducing Automata*, ed. A. W. Burks, University of Illinois Press, 1966.
5. Siringhaus H. *et al.*: *High-Resolution Inkjet Printing of All-Polymer Transistor Circuits*, *Science* 2000 290: 2123-2126
6. Pain, S.: *The chunkiest chip*, *New Scientist*, 19 October 2002, pp 60-61.
7. Das, S. *et al.*: *Producing Metal Parts with Selective Laser Sintering/Hot Isostatic Pressing*, *JoM*, 50 (12) (1998), pp. 17-20

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