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A Low-Cost Open-Source Metal 3-D Printer

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ABSTRACT Technical progress in the open-source self replicating rapid prototyper (RepRap) community has enabled a distributed form of additive manufacturing to expand rapidly using polymer-based materials. However, the lack of an open-source metal alternative and the high capital costs and slow throughput of proprietary commercialized metal 3-D printers has severely restricted their deployment. The applications of commercialized metal 3-D printers are limited to only rapid prototyping and expensive finished products. This severely restricts the access of the technology for small and medium enterprises, the developing world and for use in laboratories. This paper reports on the development of a <$2000 open-source metal 3-D printer. The metal 3-D printer is controlled with an open-source micro-controller and is a combination of a low-cost commercial gas-metal arc welder and a derivative of the Rostock, a deltabot RepRap. The bill of materials, electrical and mechanical design schematics, and basic construction and operating procedures are provided. A preliminary technical analysis of the properties of the 3-D printer and the resultant steel products are performed. The results of printing customized functional metal parts are discussed and conclusions are drawn about the potential for the technology and the future work necessary for the mass distribution of this technology.

INDEX TERMS 3-D printing, additive manufacturing, distributed manufacturing, metal processing, MIG welding, open-source, open-source electronics, open-source hardware, personal fabrication, printing, rapid prototyping, scientific hardware, scientific instruments.

I. INTRODUCTION

Additive manufacturing, commonly referred to as 3-D printing, has progressively matured technically, creating rapid growth as it has proven useful for both design, small-batch production, and potentially distributed manufacturing [1]–[8]. The *Economist* speculated that these technical advances could result in a ‘third industrial revolution’ governed by mass-customization and digital manufacturing following traditional business paradigms [9]. Traditional manufacturing and economic models may not apply as the development of open-source 3-D printers makes the scaling of mass-distributed manufacturing of high-value objects technically and economically feasible at the individual level [7], [10]–[18]. The largest class of open-source 3-D printers are self-replicating rapid prototypers (RepRaps), which manufacture 57% of their mechanical components (excluding fasteners, bolts and nuts) from sequential fused polymer deposition [11], [19], [20]. RepRaps are controlled by open-source micro-controllers such as the Arduino and Arduino-compatiable boards [21], [22] and print with polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and high-density polyethylene (HDPE) among other materials [23].

Open-source printers have seen a wide range of applications. For example, the combination of RepRaps and open-source microcontrollers running on free software enable the production of powerful scientific research tools at unprecedented low costs [24], [25]. It is now significantly less expensive to design and print research tools than to buy them, particularly if the equipment has been pre-designed; scientific equipment designs of increasing complexity are flourishing in free repositories [24]–[30]. However, the use of low-cost 3-D printing for scientific equipment has been limited to polymer and ceramic materials such as for chemical reactionware [26] and liquid handling [27], optical equipment [28], analytical instrumentation [29] and physiology laboratory components [30]. This same limitation is universal as the lack of an open-source metal alternative and the high capital costs and slow throughput of proprietary commercialized metal 3-D printers has severely restricted their deployment.

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This limitation was primarily due to economics as quality commercial 3-D printers retail for over US$500,000, severely restricting access to the technology for small and medium enterprises, the developing world and for use in most laboratories. Previous work has proposed the use of commercial robotics and welding for metal 3-D printing [31]. Building on this work, this paper reports on the development of a low-cost open-source metal 3-D printer. The bill of materials, electrical and mechanical design schematics, basic construction and operating procedures are provided. A preliminary technical analysis of the properties of the 3-D printer and the resultant steel products are performed. The results are discussed and conclusions are drawn about the potential for the technology and the future work necessary for the mass distribution of open-source 3-D metal printing.

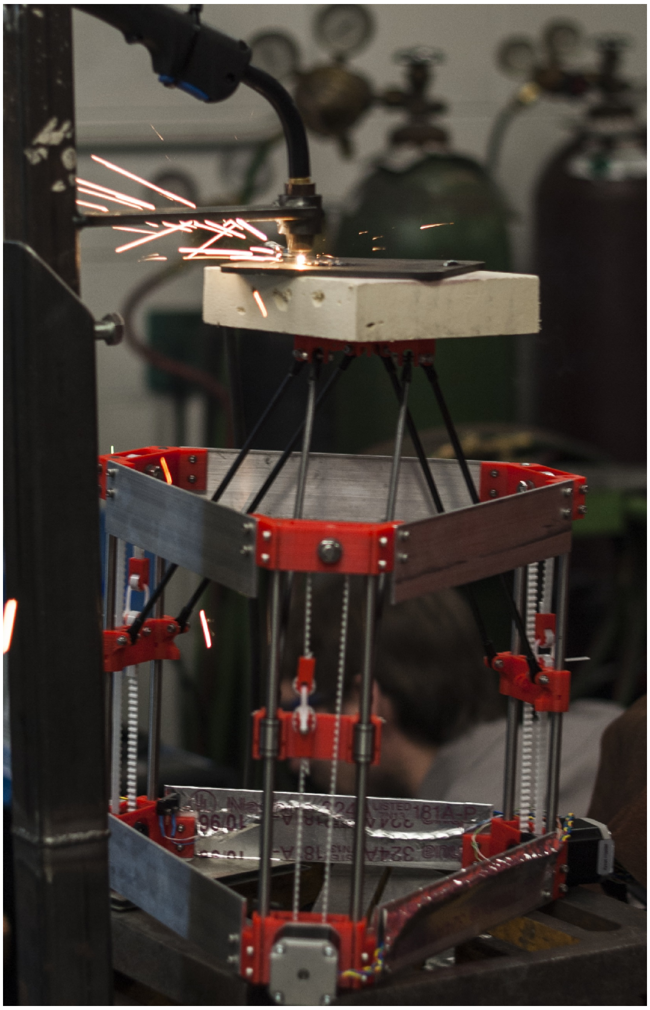


FIGURE 1. **Open-source metal 3-D printer during deposition.**

II. DESIGN, CONSTRUCTION AND OPERATION

The metal 3-D printer shown in Fig 1 consists of two units, an automated 3-axis stage, which is controlled with the open-source microcontroller and a low-cost commercial gas-metal arc welder (GMAW). The stage is a derivative of the Rostock [32], a deltabot RepRap. The design of the system adheres to the standards of the RepRap class of 3-D printers, so that it runs on free software, has free and open hardware designs, requires no specialized training in welding and existing self-replicating rapid prototypers can print the primary custom components necessary for its fabrication.

The bill of materials is shown in Table 1, which includes the component, quantity, cost and source. The electrical schematic is shown in Fig. 2 and the custom printed mechanical components are shown in Table 2.

After acquiring the BOM shown in Table 1, the stage is relatively straight forward to assemble. It consists of three identical axes that are connected together by aluminum stock to form a right equilateral triangular prism. The three identical axes consist of six printed components (motor end, idler end, pulley, carriage and a pair of belt terminators), two guide rods, stepper motor, limit switch, timing belt, linear and rotary bearings and various fasteners. A single pillar is built by attaching the motor, limit switch, idler and the two smooth rods. Two LM8UU bearings are inserted into the slots in the plastic carriage and slide onto each rod and the two 608zz bearings are fastened into the center holes in the top plastic idler. The T5 belt is looped around the pulley and idler, fastened together with a pair of belt terminators and then one terminator is fastened to the carriage.

The end effector is also a printed component and is attached to the frame by six tie rods. The tie rods are constructed from carbon fiber rods and miniature tie rod ends used in remote controlled models. The plastic end effector is protected from the heat of welding by a 1.5" thick piece of calcium silicate. The stepper motors, power supply and limit switches are wired to corresponding terminals on the microcontroller board as shown in Fig. 2, which is connected to a computer running Linux with a USB cable. Control is provided by an Arduino-based microcontroller board designed for RepRap 3-D printers and requires a host computer to operate.

The welder is setup for the wire to be used for printing by manually running beads and assuring that it is functioning correctly. Shielding gas (75% Ar/25% CO_2) is employed at a rate of 20 CFH. The stage is placed under a fixture designed to hold the welding gun perpendicular to the build surface. After leveling the stage, the distance between the build surface and nozzle is set to about 6mm by adjusting the welding gun fixture.

The entire software tool chain is freely available open-source software.(http://www.appropedia.org/Open-source_metal_3-D_printer). The open-source firmware (Repetier-firmware) translates G-code commands into pulses to the stepper motors, controlling the motion of the stage. Host software (Repetier-Host) running on a host computer provides an interface for loading G-code which it then sends to the controller. Models based upon the stereolithography (STL) standard are converted to G-code by software colloquially known as a ‘‘slicer’’, which creates patterns from uniformly thick slices of the model through the z-axis. Models can be downloaded from the Internet or created by the end user.

TABLE 1. Bill of materials for the open-source 3-D metal printer.

Item	Number	Cost (USD)	Source
All Printed Parts @ $40/kg		$ 12.00	Local RepRap
All Fasteners		$ 2.00	McMaster-Carr
M3 nut	90		
M3x10 mm screw	12		
M3x12 mm screw	48		
M3x20 mm screw	12		
M3x8 mm set screw	6		
M3 washer	102		
M8 nut	6		
M8 set screw	3		
152mm x 152mm ceramic insulation	1	$ 4.00	
Rods, bearings and ties			Amazon.com
300 mm x 8mm smooth rod	6	$ 25.00	
304.8mm carbon fiber rod	6	$ 6.00	
608zz bearings	3	$ 1.20	
LM8UU bearings	6	$ 6.00	
Small wire ties	3	$ 0.50	
Tie wire end	24	$ 8.00	
600mm T5 belt	3	$ 5.90	Polytech Design Inc.
241mm x 51mm x 4mm Aluminum plate	3	$ 114.00	Local machine shop
NEMA 17 Stepper motor (1.8 deg.,5.5kg-cm holding torque, 750mm wire)	3	$ 39.00	Kysan Electronics
Mechanical limit switch	3	$ 3.33	digikey.com
Melzi Microcontroller board	1	$ 120.00	Matterfy.com
Millermatic 140 Auto-set MIG Welder with Cart	1	$ 836.00	Miller
Power supply	1	$ 8.00	(Recycled)/ Internet
Wires	1	$ 2.00	(Recycled)/ Internet
	Total	**$1,192.93**	

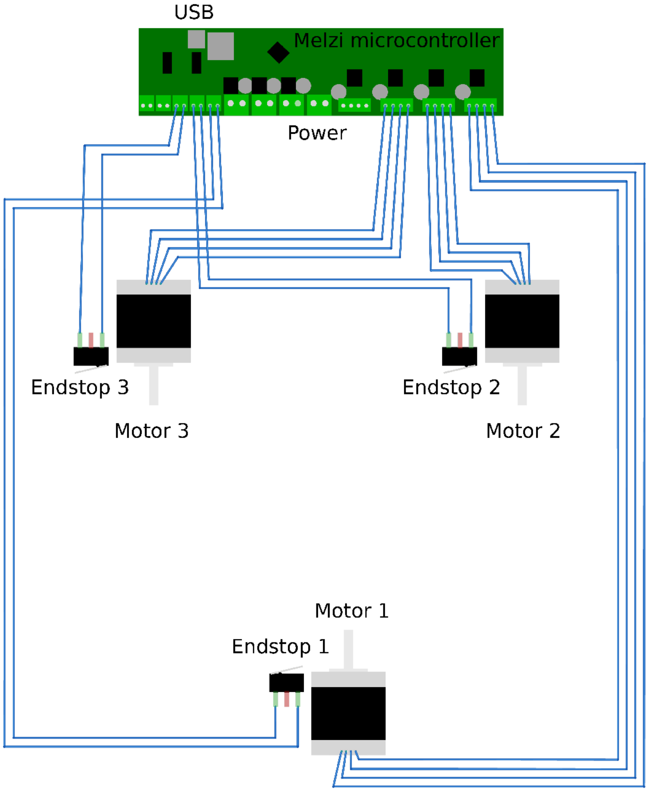


FIGURE 2. Electrical schematic of the open-source metal 3-D printer.

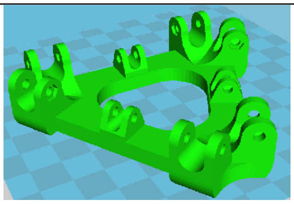
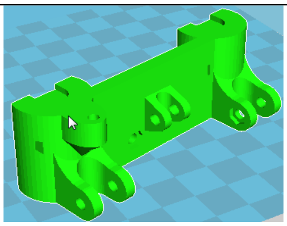
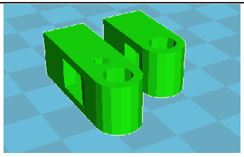
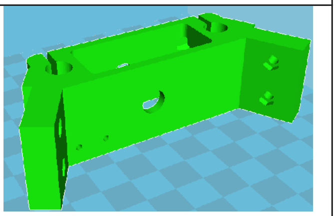
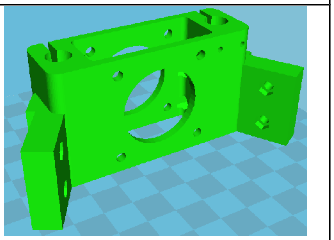
Upon receiving a print job, the printer controller moves the stage into its initial position and starts the welder feeding wire. The arc is initiated automatically and the stage moves at a relatively constant speed laying bead in the pattern dictated by G-code. The model is built in the z-direction essentially by padding one bead atop another until the entire depth of the model is created. The model can be hollow or partially to fully infilled. Upon conclusion of printing, the stage moves the piece away from the welding gun and terminates wire feed and welder current. Prints approaching an hour in length have been performed without hitting the duty cycle of the consumer-grade welder employed in this initial investigation; print duration is of course a function of the size and complexity of the model being printed.

III. METHOD

To demonstrate the utility of the device two trials are used. In the first, a Lincoln Power MIG 255 was employed at 15V, 35A with a feed rate of 80 ipm to produce a cup specimen to test for water tightness and then the specimen was sectioned, mounted, polished to 0.05 μm alumina, and etched with 3% Nital using standard metallographic methods. Vickers microhardness had a load of 300 g and a dwell time of 15 s.

The second specimen, produced with a low-cost Miller MIG, was a custom sprocket and the digital design is shown in Fig.3. The design of the sprocket was sliced using Cura 13.06.4 [33] with 1.75mm layer height, 5mm/s speed, 20mm/s translate, no infill, multiple perimeters to provide 100% infill with a concentric pattern, 2.75mm nozzle, and no retraction, which eliminates pause on layer height change. A Millermatic 140 auto-set was run at 2 with a measured wire feedrate of 3.5 cm/s. Both of these initial proof of

TABLE 2. The custom printed mechanical components of the open-source metal 3-D printer, which are designed to be printed on a RepRap.

Printed Component	Number	Image
Effector	1	
Carriage	3	
Belt Terminator	3	
End Idler	3	
End Motor	3	

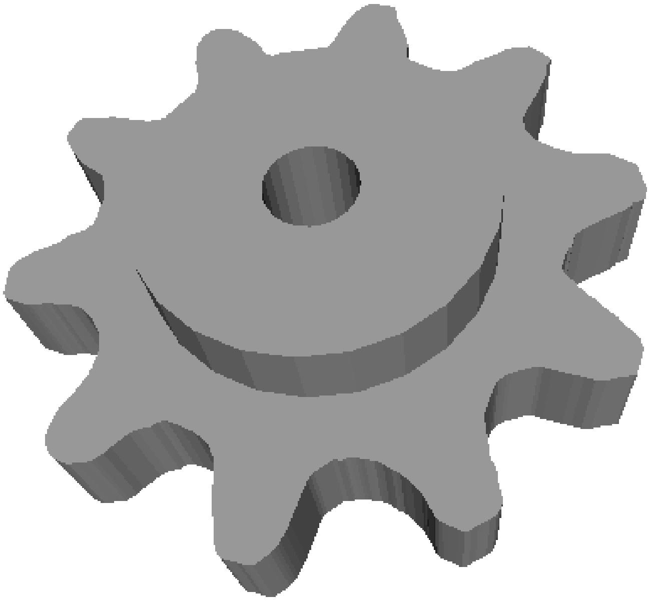


FIGURE 3. Digital design of custom sprocket modified from www.thingiverse.com/thing:10804

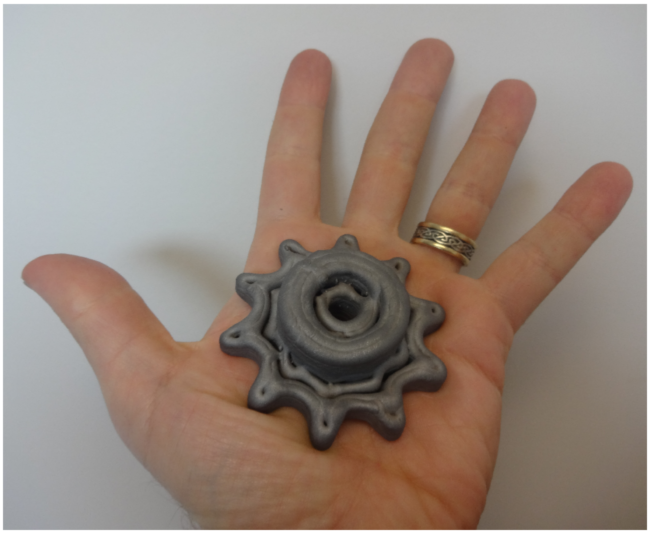


FIGURE 4. 3-D printed customized sprocket removed from the substrate.

concept trials trials used 0.024” ER70S-6 wire and 75 Ar/25 CO_2 shielding gas.

IV. RESULT

The open-source 3-D printer was successful at manufacturing impermeable metal objects and 3-D functional metal parts as can be seen in Fig. 4. The first experiment proved to be water tight and used solid carbon steel ER70S-6, which is deposited with a 75% Argon/25% CO_2 mix to prevent spatter [34]. The material has a high level of silicon and manganese, which was necessary for it to be used with slightly contaminated base materials as the sacrificial scrap steel used as substrates. The material has already been found to have excellent wetting action and puddle fluidity and is a standard steel welding material [35]. The smallest feature sizes were found when the wire feed rate was reduced while maintaining the print head velocity as a constant. As can be seen in Fig. 4, the sprocket is functional. The fill was not 100% upon printing as sliced. This can be fixed with improvements in slicing as the free software assumed the ability to change feedrate, which has not be automated into this system. Although the concept was proven there is still considerable optimization work to be done, as discussed in the future work below.

The initial experiments showed that the lower voltage and feed rate produced less heating of the workpiece, a narrower bead, and less spatter. The welding structure was nearly fully dense and had no visible cracking. Analysis of the top region of Trial 1 shows that moderate cooling led to an acicular ferrite structure (Fig. 5) that is common in low carbon welds with high manganese filler [36]. Slower cooling rates occurring at mid-section led to a polygonal ferrite structure and lower hardness (Table 3 and Fig. 5).

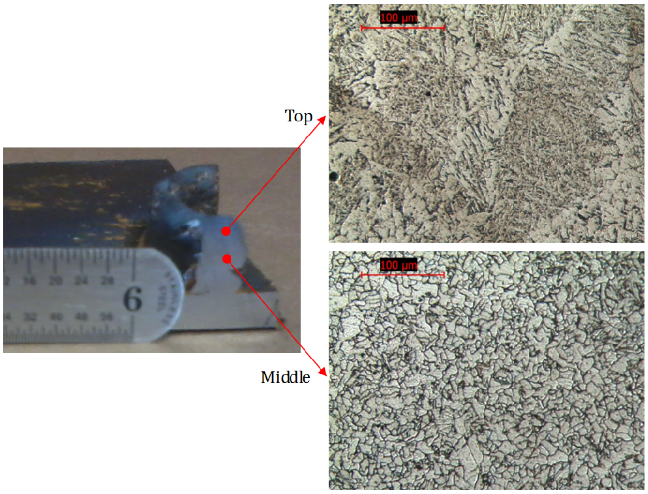


FIGURE 5. **Proof of concept trial 1 showing microstructure at top and middle of print. More rapid cooling at the top produced acicular ferrite, while slower cooling/stress relieving in the middle led to polygonal ferrite.**

TABLE 3. **Proof of concept GMAW trial 1 properties.**

Location	Cooling Rate	Microstructure	Hardness ($HV_{0.3}$)
Top	Moderate	Acicular Ferrite	187
Middle	Slow	Polygonal Ferrite	159

V. DISCUSSION

In traditional welding, the weld is ''self-quenched'' by the large surrounding thermal mass of the workpiece. This leads to modification of the phase diagram to delineate ''continuous cooling'' regions for crack susceptibility between the coherence and nil-ductility temperatures [37]. The region of cracking is offset to lower solute levels than expected from the phase diagram and requires quantifying both the thermodynamics and kinetics involved in weld solidification. Weld crack sensitivity regions have been characterized experimentally for several binary and ternary systems [37]. This is unlike the case of 3-D metallic printing, where the object is heated and remains hot during printing, so cooling rates will be much slower than welding. Therefore, it is expected that the equilibrium phase diagram will more closely represent solidification behavior during 3-D printing. This observation will allow utilization of the solidification range (liquidus-solidus) to assess cracking susceptibility similar to hot-tearing assessments in traditional metal casting. So the embrittlement range between coherence and nil-ductility will be defined as the solidification range between the liquidus and solidus temperatures.

This project successfully used an open-source RepRap variant to produce metal parts via 3-D metallic printing. Most strikingly the system can be built for less than 1/100th the cost of existing metal 3-D printers. This low cost barrier to the fabrication of the device now enables for the first time the possibility of widespread distributed manufacturing of metal components. It is likely that the economic benefit for personal production in metal will follow similar trends of 3-D polymer based printing, namely substantial consumer savings [7]. In the developing world the potential to utilize 3-D printing for sustainable development is only enhanced when considering metal [14]. At the same time there is the potential for research laboratories to begin customizing 3-D printed scientific hardware in metal inhouse, which would again expand the potential for self-fabrication of open-source hardware and accelerate the development of technology and science [25]. These developments, if they became widespread, would thus enable consumers all over the world to become producers of a much larger range of products than is currently possible. This would have widespread ramifications economically, socially and politically as it allows for a complex advanced technological 'post-scarcity' society [38]–[40] and future work is necessary to quantify these impacts. In addition, early work on the environmental life cycle analysis on both polymer 3-D printing [41] and proprietary metal 3-D printing [42] indicate that additive manufacturing has an environmental advantage as many 3-D printed products have substantially smaller embodied energy and emissions compared to conventionally-manufactured goods. All of these indicate the potential for creation of a completely new and sizable market for welding-like products to be used for fabrication of user-customized metal components in the broader consumer marketplace.

These results have proven the concept, but as this technology will evolve in a similar open-source ecosystem to that of polymer 3-D printing, rapid diffusion and improvement in the technology can be expected with applications across many types of industry and scientific disciplines.

VI. LIMITATIONS AND FUTURE WORK

The system as designed is limited in its application to desktops and is more appropriately sited in a garage or shop facility with adequate fire protection and ventilation. Significantly more personal protective equipment is necessary for safe operation than conventional polymer RepRaps including clothing to prevent burns from sparks and uv exposure, safety glasses/welding helmet, flame-resistant gloves and appropriate footwear.

There is considerable future work to develop this technology to make it appropriate for widespread deployment.

This paper can be divided into three main tasks: 1) electromechanical, 2) slicing and printer control, and 3) materials science.

A. ELECTROMECHANICAL

First, the travel speed of the stage needs to be optimized as a function of the wire feed rate and voltage for commercially available thin welding wires. This will enable improvements in resolution. Next, as the prototype developed here has two separate controls the controls of the stage need to be coupled to the MIG. In a traditional plastic RepRap 3-D printer the controls of the extruder enable precise control and feedback of both the flow rate governed by the extruder rate and the temperature. Here the wire feed rate is parallels to the extruder rate, but control of the deposition is significantly more challenging than the relatively simple control of extruder temperature and feed rate exercised by polymer 3-D printers. To complete this task two parallel paths could be followed. The first would be the design a 3-D printed unit to interface directly with standard MIG welder controls to enable control of both wire speed and voltage. The second would be to focus on integrating directly with the electronics of the MIG controls, bypassing analog user inputs altogether. The latter would provide for a streamlined new product, while the former would enable anyone with an existing welder to use it as a 3-D metal print head. The latter path could be further improved by developing a thermal or deposition rate feedback loop to enable the system to adjust MIG settings during printing. This will be important on more complex 3-D geometries to ensure that the optimal temperature is maintained at the working material.

B. SLICING AND PRINTER CONTROLLER

The current prototype can only print objects having vertical holes. A protocol for enabling bridges needs to be developed and integrated into an open-source slicer in which the power to the welder is turned off while the travel of the head and wire feed continues. After a bridge of non-melted wire is laid down the welder is returned to operation tacking it down on the far side of the bridge. In addition, for each printing material, an overhang maxima must be found and then input into the slicer to limit the overhang for a given region of deposition space. A new printer controller could be developed to enable self-tuning of the entire system and facilitate monitoring and controlling of the various additional variables associated with 3-D printing with a welder.

C. MATERIALS DEVELOPMENT AND RECYCLING

The limit on the resolution of printing using this technique is created by the wire radius, further work is needed to assess the potential for increasing resolution by decreasing the wire diameter to less than 0.024", the prevalent smallest diameter material currently available. These wires can be made of a wide range of various metals and alloys, for example aluminum. Highly recycled aluminum beverage containers could be utilized as a form of already distributed feedstock in 3-D metal printing. 3004 aluminum is used for the bottom and sides of the can and comprises about 75 wt% of the can, while the top is 5052 aluminum and is about 25 wt% of the can [43]. The composition of the remelted cans has a magnesium content that should produce hot cracking [43]. New alloys need to be developed for 3-D printing using remelted cans as feedstock while assuring minimal additions to avoid hot cracking. It is likely that a 2-3 wt% Mg addition will be sufficient to eliminate heat cracking, making beverage cans feasible feedstock for 3-D printing.

VII. CONCLUSION

This paper has successfully provided the proof of concept of a <$2000 open-source metal 3-D printer. Steel components could be printed water tight with a single exterior layer. In addition, the 3-D printing of customized functional mechanical parts from standard STL files was demonstrated. The low-cost barrier to the fabrication of the device and the libre source plans now enables for the first time the possibility of widespread distributed manufacturing of metal components. There is a distinct potential for the creation of a completely new and sizable market for welding-like products to be used for fabrication of user-customized metal components in the broader consumer marketplace. As this technology is likely to follow a similar evolutionary path to that of polymer open-source 3-D printing, rapid diffusion and improvement in technology can be expected with applications across many types of industry and scientific disciplines.

VIII. ACKNOWLEDGMENT

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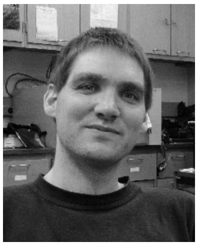

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