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Applications of Open Source GMAW-Based Metal 3-D Printing

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Abstract: The metal 3-D printing market is currently dominated by high-end applications, which make it inaccessible for small and medium enterprises, fab labs, and individual makers who are interested in the ability to prototype and additively manufacture final products in metal. Recent progress led to low-cost open-source metal 3-D printers using a gas metal arc welding (GMAW)-based print head. This reduced the cost of metal 3-D printers into the range of desktop prosumer polymer 3-D printers. Consequent research established good material properties of metal 3-D printed parts with readily-available weld filler wire, reusable substrates, thermal and stress properties, toolpath planning, bead-width control, mechanical properties, and support for overhangs. These previous works showed that GMAW-based metal 3-D printing has a good adhesion between layers and is not porous inside the printed parts, but they did not proceed far enough to demonstrate applications. In this study, the utility of the GMAW approach to 3-D printing is investigated using a low-cost open-source metal 3-D printer and a converted Computer Numerical Control router machine to make useful parts over a range of applications including: fixing an existing part by adding a 3-D metal feature, creating a product using the substrate as part of the component, 3-D printing in high resolution of useful objects, near net objects, and making an integrated product using a combination of steel and polymer 3-D printing. The results show that GMAW-based 3-D printing is capable of distributed manufacturing of useful products for a wide variety of applications for sustainable development.

Keywords: gas metal arc welding; metal 3-D printing; open-source; low-cost; steel

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1. Introduction

Most of the metal 3-D printers available on the market are for high-end applications, which require expensive equipment and use relatively dangerous fine metal powders [1]. Due to the cost and the complicity of the technology, it is inaccessible for small and medium enterprises (SMEs), fablabs, and individual makers who are interested in the ability to prototype and make final products in metal using additive manufacturing technology. Following the tradition of the self-Replicating Rapid-prototyper (RepRap) [2–4], a low-cost open-source metal 3-D printer was developed with a gas metal arc welding (GMAW)-based print head, which radically reduces the costs of metal 3-D printers to less than $1200 [5]. The open source metal 3-D printer uses readily available weld filler wire as the source of material and the initial designs have been improved upon with integrated monitoring [6] of the welding system [7]. In addition, recent work has shown approaches to reuse substrates which help to reduce costs, energy, time, and the environmental impact of manufacturing [8,9]. These previous works showed that GMAW-based metal 3-D printing has a good adhesion between layers and is not porous inside the printed parts, but did not proceed far enough to demonstrate its applications, e.g., only test cubes and dog bones were printed for mechanical testing. Many studies have been done on the 3-D weld deposit-based process [10–13] and investigated thermal properties and stresses [14–17], toolpath planning [18–21], bead-width control [22,23], mechanical properties [24,25], and support for overhangs [26]. These previous works clearly demonstrated that GMAW-based metal 3-D printing prints solid objects with low porosity, but did not proceeded far enough to directly demonstrate applications.

In this paper, the utility of the GMAW approach to 3-D printing will be investigated using a low-cost open-source metal 3-D printer and a converted Computer Numerical Control (CNC) router machine to make useful parts over a range of applications including (1) fixing an existing part by adding a 3-D metal feature (e.g., re-manufacturing); (2) creating a product using the substrate as part of the component; (3) 3-D printing in high resolution of useful objects; (4) near net objects; and (5) making an integrated product using a combination of steel and polymer 3-D printing. These applications will be discussed in the context of sustainable development.

2. Materials and Methods

The design of the low-cost open-source metal 3-D printer [5,7] is inspired by the Rostock style delta RepRap [27]. However, it uses a stage printing setup allowing for stationary heavy toolheads [28,29] while automatically controlling the movement of a substrate with three-axis control under a fixed perpendicular weld gun printer head (Figure 1C). The motion controls are managed by an Arduino-based microcontroller and the free and open source 3-D motion control software called Franklin [30]. Franklin also controls the welder (e.g., on for printing and off for traveling). A Millermatic 190 welder (Miller, Appleton, WI, USA), ER70S-6 steel wire, and shield gas of RC25 (75% Ar and 25% CO_2) were used for the experiments. Printing is performed on a re-useable substrate of low carbon steel with dimensions of 127 × 127 × 6 mm. The stage that holds a substrate is covered with cement board and then an aluminum plate (Figure 1C) to accelerate the transfer heat away from the printed part.

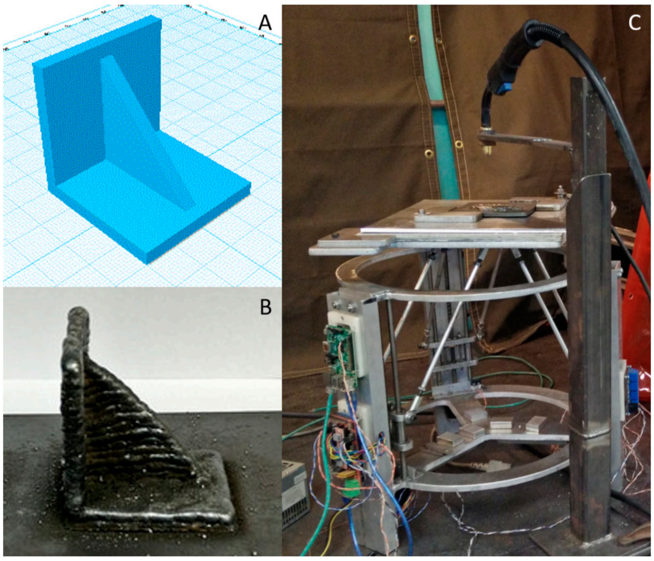

Figure 1. A bracket and metal 3-D printer (**A**) 3-D model; (**B**) metal 3-D printed part on substrate, where the substrate is a model for an existing part; and (**C**) the set-up of an open-source GMAW-based metal 3-D printer.

For a 3-D model larger than 127 mm in any dimension, a CNC Router Parts machine was adapted as a GMAW 3-D printer) [31]. A Benchtop PRO CNC Machine Kit (North Bend, Washington, DC, USA) was adapted to be used in this research [32]. The work area is 25″ × 25″ and the Z clearance is 7″. The resolution or repeatability is ±0.001″ or ±0.0254 mm. The Millermatic 190 GMAW is also used for the filament deposition tool. The weld gun is mounted to the tool holder of the machine as the printer head and modified to accept a control signal. The control unit is modified to add output signal wires to the weld gun connection to turn the welder on and off. Substrates of the same low carbon steel with dimensions of 254 × 254 × 6 mm were then used. The aluminum plate with the same size of the substrate is placed under the substrate. Here, the substrate is also held down at four corners during the printing and the moving weld gun is mounted to the tool holder. The welder and the shield gas are the same as in the delta printer above. Mach3 CNC33 software (v. 3.043.062) [33] was used to communicate to the control unit via an Ethernet cable.

MOSTMetalCura [34] is a customized version of CuraEngine for metal 3-D printing. It slices a 3-D model into 2-D layers and generates toolpaths for each layer. The produced toolpaths are recorded as G-Code. Franklin and Mach3 use G-Code instructions to control the movements of the printers. MOSTMetalCura has added the abilities to turn on and turn off the welder through G-Code, to keep the status of printing or welding, to set how long to pause between layers for the printed part to cool down, and to recommend the wire feed speed setting on the welder (specific for Millermatic 190, for other welders an equation for wire feed speed in MOSTMetalCura would need to be edited). The important settings for MOSTMetalCura are infill line width or bead width, layer height, printing speed, and material diameter.

From a 3-D model, which can be downloaded from free design repositories or created by open-source CAD software (e.g., OpenSCAD [35]), MOSTMetalCura generates a G-Code file from the 3-D model. The settings for open-source GMAW-based metal 3-D printing are shown in Table 1. Connecting to Franklin through a browser via a web service, Franklin loads the G-Code file and verifies instructions inside the file. When the printing is started by the user, Franklin translates each G-Code instruction and controls the stepper motors on the MOST's open-source 3-D metal printer to move the substrate as commanded. On the CNC converted 3-D printer, Mach3 is acting in a similar way to Franklin, except that the substrate is stationary and the weld gun is moving as directed by the G-Code. The printing is continued with pausing between layers until the whole model is printed.

Table 1. Settings for open-source GMAW-based steel 3-D printing.

Settings	Value (Unit)
Voltage on the welder	5 (unitless)
Wire feed rate on the welder	30 (unitless)
Distance between nozzle and substrate	8 (mm)
Wire sticking out from contact tip	5 (mm)
Printing speed	7 (mm/s)
Layer height	2 (mm)
Line or bead width (±0.03)	~1 (mm)
Shield gas	25 (CFH)

3. Results

Applications of GMAW-based metal 3-D printing are successfully demonstrated by the following printed parts, as seen in Figures 1–5. Parts and products, which would be of interest to SMEs or those in developing regions, are focused on here because of the low-cost of the system. The bracket, the hoe, and the chisel were printed on the open-source delta-style metal 3-D printer and the horseshoe, ring stand holder, and axe head were printed on the CNC machine. The handle of the axe was polymer 3-D printed on a larger CNC machine [36] converted to use Franklin (note all such CNC machines could be converted to run free Franklin). These 3-D models as STL files can be found at https://osf.io/bbbtd [37].

1. The system can be used for fixing or printing onto an existing part. A bracket is an example used here where it was printed on the substrate as an existing part (Figure 1). Holes can be printed or

drilled on the open end of the bracket, so another part can be attached and secured with nuts and bolts. This can be utilized in fixing broken equipment. A different design of a bracket can optimize its strength, stiffness, size, and weight. For example, General Electric (GE) held a contest for such a bracket design for a jet engine in 2013 [38]. Similar bracket fixes can be useful for a wide range of applications including solar photovoltaic racking [39].

2. The system can be used to create a product using metal 3-D printing and a substrate as an integral part of the product. For example, a hoe can be made by 3-D printing a cylinder on the substrate (Figure 2B). Then, the substrate is cut into a shape of a hoe and sharpened on the edge opposite the printed cylinder (Figure 2C). A wood or a polymer 3-D printed stick can be used as a handle for the hoe. Being able to manufacture such a product in an isolated rural community can be considered appropriate technology and can foster sustainable development [40–42]. The ability to manufacture metal objects significantly expands the utility of 3-D printing for small farmers in the developing world [43].
3. The system is capable of a higher resolution than previous attempts at GMAW-3-D printing [5]. A high resolution chisel model (Figure 3A) and chemistry laboratory support ring model (Figure 3D) are used to demonstrate this capability. The printed part is ready to use with minimal machining (Figure 3C,F). In Figure 3G, the finished metal 3-D printed ring support was used in a lab. This technique can be applied in similar situations that require a custom part. For example, in the design of open source scientific equipment [44–46], a custom size of a ring support or a vial holder for a hot plate can be easily designed and printed. A model with small details can be printed as long as they are not smaller than 1 mm.
4. Near-net shape objects can be fabricated with the system. An example of this is a horseshoe (Figure 4), which needs to be customized for specific horses, so it is suitable for metal 3-D printing. The printed part is a near-net shape, so it needs finish machining.
5. Finally, fully functional integrated products can be fabricated using a combination of metal and polymer 3-D printing. Here, an axe head was 3-D printed in steel (Figure 5) and a handle was 3-D printed in nylon. A combination process like this can be used to remotely manufacture similar open source instruments such as a hammer or other hand tools that would be useful in the developed and developing world [47,48].

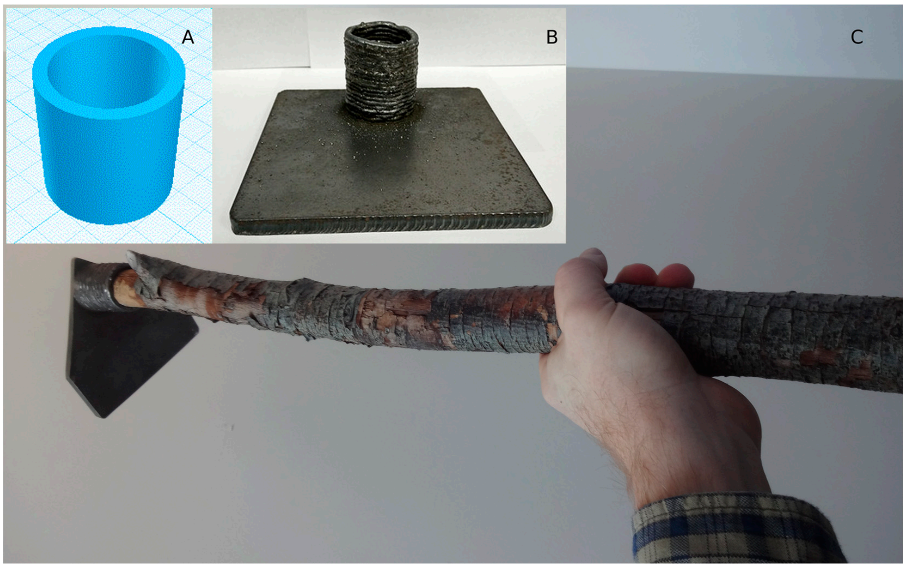

Figure 2. A hoe (**A**) 3-D model of handle hold; (**B**) metal 3-D printed part on substrate; and (**C**) finished hoe, cut and mounted to wooden handle.

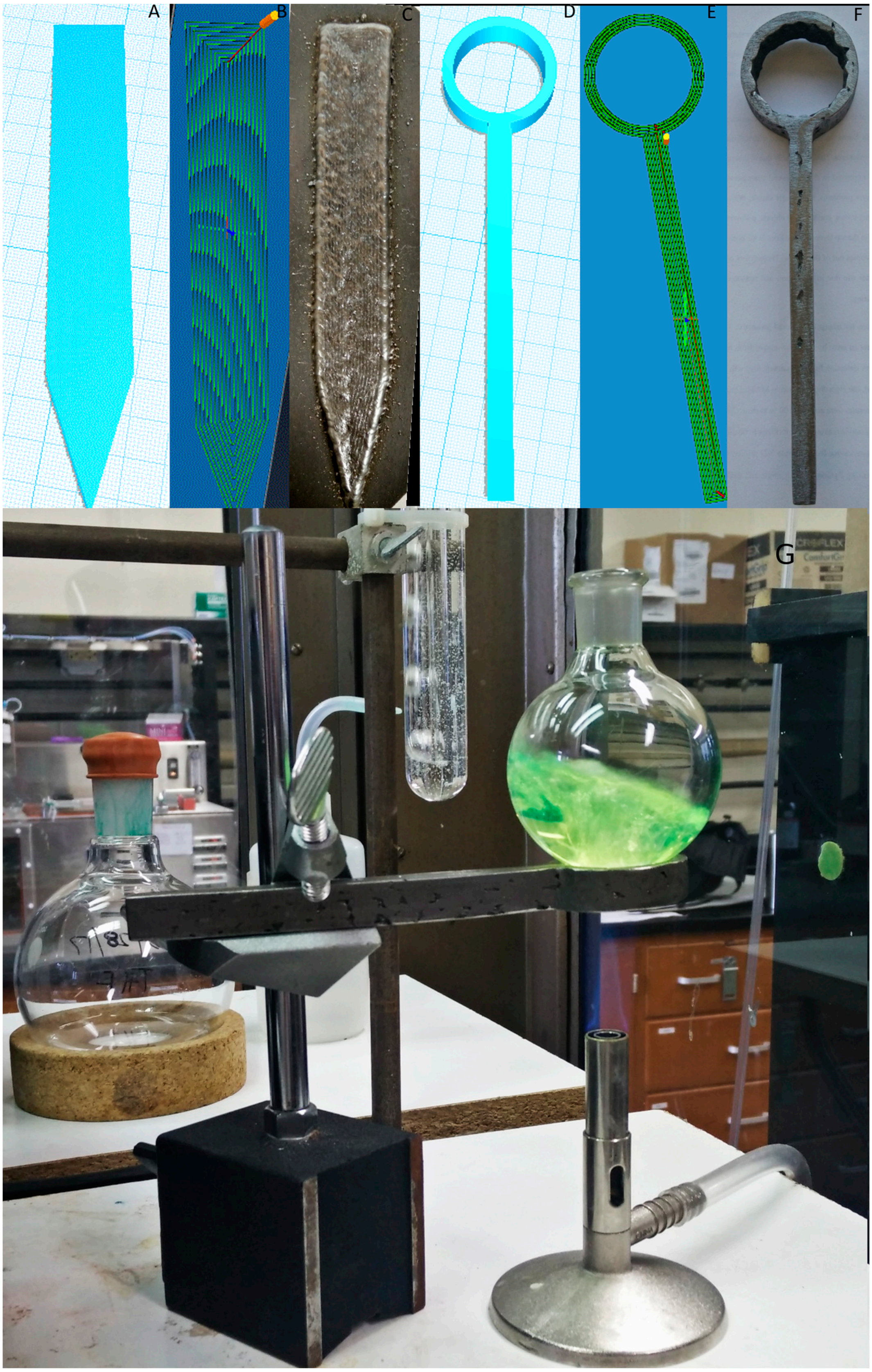

Figure 3. (**A**) 3-D model; (**B**) toolpath; (**C**) metal 3-D printed part on substrate; (**D**) 3-D model; (**E**) toolpath; (**F**) metal 3-D printed part; and (**G**) ring support used in a chemistry laboratory.

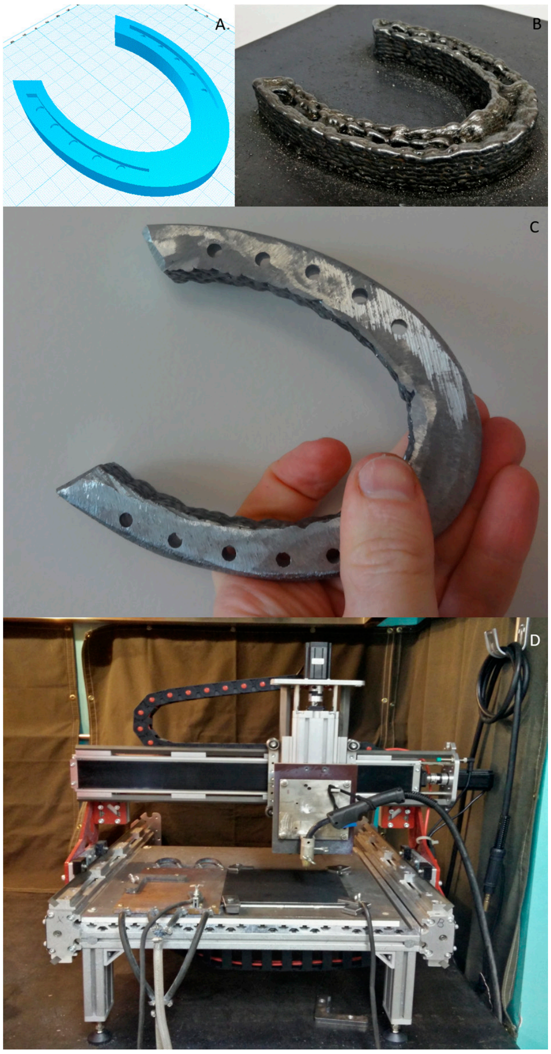

Figure 4. A horseshoe and CNC Router Parts 3-D printer conversion (**A**) 3-D model; (**B**) metal 3-D printed part on substrate; (**C**) finished part; and (**D**) a converted CNC Router Parts metal 3-D printer.

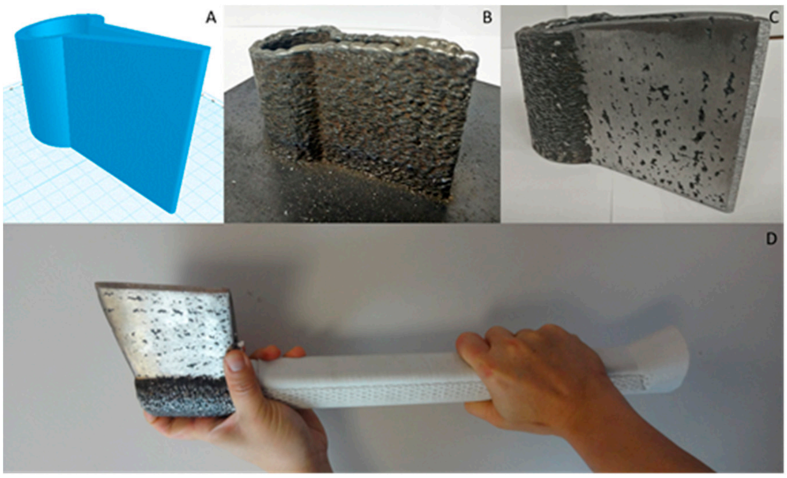

Figure 5. An axe (**A**) 3-D model; (**B**) metal 3-D printed part on substrate; (**C**) finished part (axe head); and (**D**) integrated product using metal and polymer 3-D printing for the handle.

4. Discussion

From the results, it is clear that low-cost GMAW-based metal 3-D printing can be applied to many real-life problems encountered in sustainable development. First, the technique can be used to repair or add functionality to an existing steel product. As in the case with the bracket, the settings can be adapted to leave the part on the substrate of an existing part. Thus, if, for example, a bracket were to break off a tractor part, the tractor could be repaired by replacing the broken bracket on the main component or a new bracket could be added to a part to improve the mechanical assembly of the assembly. There are many applications for this functionality, which include; repairing damaged parts [49–51] and customizing or adding to an existing object [52]. This is particularly important in the field in isolated regions (e.g., for development for rural farmers).

A close application to this functionality is to use the substrate and a 3-D printed design to create a new product, as is shown with the hoe (Figure 2). The printed metal has a good adhesion to the substrate, so they became one part if no substrate release mechanism was used. This kind of application is useful whenever the end product can be primarily manufactured from a plate of steel. Although the entire hoe could have been printed without using the steel substrate, the manufacturing time is considerably reduced (roughly two hours) by incorporating the substrate. Other applications of this method include similar products, such as a rake, a flag pole stand, and a flute stand, etc.

As can be seen in Figure 3, the process is capable of printing in relatively high resolution for the cost of the process—down to 1 mm lines. This functionality is useful for making highly detailed steel parts such as a gear.

The most useful current application of open source GMAW-based 3-D printing, however, is the manufacturing of near-net shape objects. This is demonstrated in Figure 4 with the horseshoe. The near-net shape market, for example, is the fastest growing market for hot isostatic pressing for a wide range of applications [53] and is seen in many industries and has many applications. For example, in the auto industry, when a needed part is no longer available or in short supply, the part can be 3-D printed [54–56]. Printing custom brackets on high volume stampings or extrusions would also be valuable for automotive applications. The added flexibility to enable a small amount of machining from an object that is a near-net shape cuts down on material waste, embodied energy, machining time, and economic costs.

The combination of metal and polymer 3-D printing as shown in Figure 5 can be applied to produce many things that need both metal and plastic. Many tools have a metal part with plastic handles, such as a screwdriver, knife, and gardening tools, etc.

Many 3-D models that are available, but commonly printed only in plastic, would have improved performance if metal printing technology such as this were employed. However, as the resolution of printing is constant at 1 mm, if there are details in a 3-D model that are smaller than that, they will be lost. So only near-net shape functionality is available for the majority of readily available 3-D models (made for 100 micron resolution) unless they are scaled up. The smaller details would need to be post machined to the print. A 3-D model that is not a full millimeter in any dimension will also result in a little bit smaller or bigger printed part (e.g., 0.5 mm designed wall will result in 1mm print). If there is an angle of less than 45 degrees of the z-axis in a 3-D model, the staircase effect will appear at the angle in the model.

A big 3-D model with a large volume to be filled will result in a long pause time between layers to let the printed layer cool down before printing the subsequent layer. Otherwise, the heat inside the printed layers can cause defective surfaces for the next layer. If a model can be hollow, it will reduce the pause time by half. For example, the axe head would require 30 min of pause time between layers if it were 100% filled, but it is hollow, so only 15 min needed. One approach recently shown by Lu et al. to partially address this challenge is to use active cooling [57]. Cooling down the part reduces the pause time necessary for the 3-D printer in between layers. In addition, Lu et al.'s results indicate that the formability of metal parts fabricated with an open-source wire and arc additive manufacturing (WAAM) system were improved with compulsory cooling [57].

Testing of the mechanical properties of the printed steel has been evaluated previously [58]. Haden et al. investigated the mechanical properties of wire and arc additive manufacturing (WAAM) of both stainless steel 304 and mild steel ER70S; the latter of which was used in this study. They found that wear and hardness depended on the direction of deposition and in Z height, due to variations in local thermal histories of the metal; however, the yield and ultimate strength were about the same and were within error or slightly above wrought values reported in the literature [58]. Future work is needed for statistical certainty, as well as following up on their results that indicate that careful toolpath planning can be used to control and design localized material properties in the WAAM/GMAW process [58]. In addition, the tensile, compressive, and microstructural properties of GMAW 3-D printing of aluminum alloys was evaluated by Haselhuhn et al. [59] for common aluminum weld filler alloys (ER1100, ER4043, ER4943, ER4047, and ER5356), as well as for novel hypoeutectic aluminum–silicon alloys [60]. The results showed that the porosities in all test specimens were less than 2%, with interdendritic shrinkage in 4000 series alloys and intergranular shrinkage in 5356 [59]. Overall, the 3-D printed 4000 series alloys performed better and showed similar or superior mechanical properties in comparison to standard wrought and weld alloys [59]. GMAW-based 3-D parts printed from aluminum alloys have shown similar mechanical properties to those fabricated using more conventional processing techniques. Overall, the results of past studies on GMAW or WAAM mechanical properties of steel and aluminum alloys indicated that 3-D printed metal parts from these techniques can be expected to be equivalent (and perhaps superior with careful tuning to control heat treatment) to conventionally manufactured parts from the same material. However, future work is needed to verify these results in a large number of samples and geometries.

It should be pointed out here that the examples of functionality given above are simply that—just examples of relatively simple geometries. Far more complex geometries are possible and the range of applications already available to this class of machines is already in the millions based on the number of free designs available in Internet repositories. It is also possible to manufacture some of these items using more conventional blacksmithing (e.g., a hoe can be fabricated with a metal plate and spot welding a cut piece of pipe to it). However, with this technique, custom equipment of any type can be made using only wire and electricity as feed stocks and without the specialized skills of the blacksmith to enable digital reproduction down to 1mm in resolution in steel.

In addition, the CNC machine in this experiment does not have a consistency of moving speed between moving along the x- or y-axis and moving diagonal. When moving along the x- or y-axis, it has a speed that is a little faster than when moving diagonally, which caused a rougher surface and a larger layer height. To avoid the different speed, a 3-D model can be rotated or a shape (e.g., cylinder) that requires diagonal moving can be used. Future work is needed to determine if this machine-related artifact could be removed with the use of open source firmware. In addition, future work is needed to further improve the resolution to below 1 mm. A finer resolution would provide the ability to achieve a thinner layer height that would diminish the staircase effect and enable a greater range of applications. A better method is needed to release the heat from the printed part during deposition with the use of active cooling, such as a water-cooled chill plate, which would cut down the waiting time between layers and thus accelerate part production. Finally, methods of monitoring 3-D printing with GMAW print heads are needed for real time correction and control (e.g., by adapting scanning and capture technology [61] or applying low cost webcam techniques developed for polymer-based RepRap systems [62]) and eventually using advanced techniques (e.g., ultrasonic vibrations) to alter/improve the quality of the metal print in real time [63].

5. Conclusions

This paper has successfully shown applications of low-cost open-source GMAW-based metal 3-D printing, which are relevant to sustainable development. The results show that GMAW-based 3-D printing is capable of distributed manufacturing of useful products by SMEs and individual makers for a wide variety of applications. Metal products and parts can be designed and created using this technology and the low-cost and open-source advantages make it available to everyone. This also gives the user the flexibility to customize the hardware and software for other uses.

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Conflicts of Interest: The authors declare no conflict of interest.

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