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Article

# Open-Source Grinding Machine for Compression Screw Manufacturing

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**Abstract:** Some of the most promising distributed recycling and additive manufacturing (DRAM) technical systems use fused particle fabrication (FPF) or fused granular fabrication (FGF), where compression screws force post-consumer waste plastic through a heated nozzle for direct 3D printing. To assist the technical evolution of these systems, this study provided the details of an invention for a low-cost, easily replicable open-source grinding machine for compression screw manufacturing. The system itself can be largely fabricated using FPF/FGF following the self-replicating rapid prototyper (RepRap) methodology. This grinding machine can be made from a cordless cut-off grinder and < $155 in parts. The new invention is demonstrated to be able to cut custom screws with variable (i) channel depths, (ii) screw diameters, (iii) screw lengths, (iv) pitches, (v) abrasive disk thicknesses, (vi) handedness of the screws, (vii) and materials (three types of steel tested: 1045 steel, 1144 steel, and 416 stainless steel). The results show that the device is more than capable of replicating commercial screws as well as providing makers with a much greater flexibility to make custom screws. This invention enables the DRAM toolchain to become even more self-sufficient, which assists the goals of the circular economy.

**Keywords:** grinding machine; open hardware; open-source hardware; open-source appropriate technology; compression screw; grinding; cylindrical grinding machine; recycling; material extrusion; angle grinder

## 1. Introduction

The proven effectiveness of the free and open-source software movement [1,2] is being replicated by the open-hardware community [3] with an approximately 15-year lag [4]. Open hardware is accelerated by platform technologies such as the Arduino electronics rapid prototyping platform [5,6] and its derivative, the self-replicating rapid prototyper (RepRap) project [7–9]. The goal of the RepRap project is to create 3D printers that can 3D print their own components [7–9]. Open-source RepRap material extrusion-based 3D printing substantially enlarged access to additive manufacturing (AM) due to radical cost declines and an enormous expansion in the market for desktop 3D printing [10,11]. RepRap technology in turn catalyzed millions of free and open-source 3D-printable designs and created a consumer (or prosumer) form of distributed manufacturing [12–14]. RepRaps and their derivatives are now used to manufacture a wide range of products from household items [15–18] to high-end scientific tools [19–23], generally far less expensively than available commercially [24–26]. The business community understands the widespread impact this potential shift in manufacturing represents [27–33], whether the 3D printers are used in libraries [34–36] or at consumers' own homes [37,38]. It appears that all types of products used at the beginning of life, such as toys [39], to those generally used by the elderly, such as arthritic adaptive aids [40] can save consumer money by distributed manufacturing. This is remarkable because these savings are based on fused filament fabrication (FFF) and commercial 3D printing filament is generally sold for ~$20USD/kg while the cost of the raw materials of virgin plastic pellets is only $1–5 USD/kg.

Previous research has shown that it is both technically viable and less expensive to use distributed manufacturing to fabricate filament with an open-source waste plastic extruder (or recyclebot) [41,42]). Combined, these concepts provide for the possibility of distributed recycling and additive manufacturing (DRAM) in a circular economy [43–46]. The environmental benefits of both distributed recycling [47–49] and distributed manufacturing [50,51] are clear because the embodied energy and pollution from transportation between processing steps are eliminated. Substantial research has shown that many waste polymers can be recycled into filament for FFF:

- polylactic acid (PLA) [42,52–56];
- acrylonitrile butadiene-styrene (ABS) [44,57–59];
- elastomers [15];
- high-density polyethylene (HDPE) [41,60,61];
- polypropylene (PP) and polystyrene (PS) [61];
- polyethylene terephthalate (PET) [62,63];
- linear low-density polyethylene (LLDPE) and low-density polyethylene (LDPE) [64];
- polymer blends [65], composites [66] and various mixtures with waste wood fiber [47,63,67,68].

Unfortunately, for all of these polymers, the melt solidification during the recyclebot fabrication of filament degrades the mechanical properties of the resultant 3D-printed object [69,70], which limits recycling following this method to approximately five cycles before mechanical reinforcing is needed [52,53].

It is possible, however, to eliminate the filament entirely for material extrusion-based AM by grinding post-consumer waste with an open-source waste plastic granulator [71] to make flakes or particles and directly printing from these, regrind, or shreds of recycled plastic with fused particle fabrication (FPF) (also sometimes called fused granular fabrication (FGF)). FPF/FGF 3D printers are being developed in the academics [71–76], maker communities [77–79], and by businesses (e.g., Cheetah Pro, David, Erecto-Struder, GigabotX, and PartDaddy). The GigabotX, an open-source industrial 3D printer, has, for example, been demonstrated to FPF/FGF print recycled PLA ABS, PP, PET and polycarbonate (PC) [80–83]. In general, FGF/FPF 3D printers are far more expensive than their FFF counterparts in large part due to the expense of a precision machined compression screw. These compression screws also impact the cost of commercial recyclebots (e.g., the filabot extruder screw costs $749 USD [84], which is approximately the cost of an entire open-source recyclebot). In addition, preliminary results for desktop-sized open-source FPF 3D printers are promising [85], but the ability for the printer to handle larger pellets is restricted because of the commercially-available small-scale compression screw designs. In order for DRAM to reach its fullest potential, a low-cost open-source method is needed to drive down the costs of compression screws for both FPF/FGF 3D printers and recyclebots.

To fulfill this need, this study provides the designs for a low-cost, easily replicable open-source grinding machine for compression screw manufacturing. Following the RepRap methodology, many of the components of this grinding machine can be fabricated using FPF/FGF. This new invention is tested and characterized in terms of costs, screw section length able to be cut, potential diameter rod range, and battery-life test for grinding screws 110 mm in length. Then validation tests were performed to demonstrate screw grinding with variation in (i) channel depth, (ii) screw diameter, (iii) screw length, (iv) change in pitch, (v) abrasive disk thickness, (vi) the handedness of the threaded rod, vii) and three types of steel, 1045 steel, 1144 steel, and 416 stainless steel. The results are presented and discussed in the context to adding this machine to the DRAM toolchain by enabling makerspaces, fab labs, companies and universities to fabricate compression screws rapidly for approximately the cost of the bar stock.

## 2. Materials and Methods

### 2.1. Design

The design for this compression screw manufacturing machine was inspired by the common lathe machine used in wood and metal working. The design followed the design procedure for open-hardware development [3,86,87]. The components used were chosen for both their functionality and cost efficiency. The bill of materials for constructing the machine is provided below in Table 1 and a list of all tools used are shown in Table 2. A detailed bill of materials (BOM) with all manufactured components used can be found in [88] in addition to all design files.

**Table 1.** Bill of Materials (BOM) for the Open-Source Grinding Machine for Compression Screw Manufacturing.

| Type | Item | Count | Length (Inches) | Cost | Purpose |
|---|---|---|---|---|---|
| Raw Material | PLA filament ~1 kg | 1 | | $19.00 | Material used to 3D print all components other than the belt |
| Raw Material | Nijatek Ninjaflex 85 A~12 g | 1 | | $1.08 | 3D-printed belt to connect threaded rod and chuck pulleys |
| Hardware | Conduit | | 49.5 | $2.68 | Rails for the X and Y sliders to move on |
| Fastener | M8 × 30 mm hex head bolt | 28 | | $6.40 | Axle and secures M8 Bearings |
| Fastener | M8 nylon insert locknut | 28 | | $2.93 | Secures M8 Bearings |
| Fastener | M7 × 16 mm hex head bolt | 8 | | $2.17 | Mounting the flange bearings |
| Fastener | M7 hex nut | 8 | | $0.36 | Mounting the flange bearings |
| Fastener | M3 × 12 mm | 36 | | $3.12 | Fasten 3D-printed parts |
| Fastener | M3 hex nut | 36 | | $2.00 | Fasten 3D-printed parts |
| Fastener | 5/16″–18 × 1–1/4″ grade 5 hex head bolt | 1 | | $0.17 | Mounting angle grinder (dependent on angle grinder used) |
| Linear Motion | 3/8″–16 left-hand threaded rod | | 36 | $21.24 | Moves X slider for left-hand threaded compression screws |
| Linear Motion | 3/8″–16 left-hand threaded hex nut | 9 | | $1.81 | Moves X slider for left-hand threaded compression screws |
| Linear Motion | 3/8″–16 right-hand threaded rod | | 36 | $9.18 | Moves X slider for right-hand threaded compression screws |
| Linear Motion | 3/8″–16 right-hand threaded hex nut | 9 | | $0.79 | Moves X slider for right-hand hex nu compression screws |
| Hardware | 10 mm self-aligning pillow block flange bearing | 4 | | $20.18 | Secures threaded rod and chuck |
| Hardware | 3–16 mm drill chuck with SDS-plus shank | 1 | | $19.00 | Holds the stock material being machined |
| Hardware | 608 ZZ bearings | 24 | | $8.40 | Linear motion, stock support |
| Raw Material | 20″ × 20″ Baltic birch | 3 | | $12.00 | Frame of the machine |
| Fastener | Flat-head wood screws #6 × 3/4″ in length | 36 | | $1.50 | Secures individual pieces of plywood together |

**Table 1.** *Cont.*

| Type | Item | Count | Length (Inches) | Cost | Purpose |
|---|---|---|---|---|---|
| Fastener | Flat-head wood screws #6 × 1–1/4″ in length | 4 | | $0.22 | Secures the plywood subassemblies |
| Fastener | Wood glue 8OZ. (Titebond II) | 1 | | $4.00 | Secures all plywood pieces together |
| Consumable | Type 27 ceramic grinding wheel 4–1/2″, 1/4″ thickness | 2 | | $12.00 | Machining the round stock |
| Consumable | 4–1/2″ aluminum oxide cut-off wheel | 1 | | $3.00 | Cut conduit, threaded rod, and round stock |
| Total | ° | | | $153.23 | |

**Table 2.** Tools Used for the Fabrication of the Open-Source Grinding Machine for Compression Screw Manufacturing.

| Description | Use |
|---|---|
| Desktop FFF 3D printer | Part manufacturing |
| CNC wood router with 20″ × 20″ work area | Cut out plywood components |
| 3175 × 17 mm compression wood end mill | Used in CNC wood router to cut out plywood components |
| 4–1/2″ angle grinder | Cutting metal conduit, round stock, and used in the machine |
| Construction speed square | Frame construction, round stock setup |
| 2.5 mm hex key | Fastening M3 socket cap screws |
| 2 mm hex key | Used on the flange pillow block bearings |
| 13 mm socket | Fastening M8 hardware |
| Ratchet | Tightening fasteners |
| 13 mm box wrench | Fastening M8 hardware |
| 9/16″ box wrench | Used for tightening threaded rod nuts |
| Crescent wrench | Tightening jam nuts on threaded rod and with free-end support |

All 3D-printed components are printable on most desktop 3D printers using polylactic acid (PLA) and thermoplastic elastomer (TPE), as seen in Appendix A Table A1.

The frame of the machine is currently manufactured out of plywood for its low cost and ability to conform to the dimensional constraints of the 3D printer. Linear motion relies on the use of a metal pipe. The design files were developed parametrically such that the dimensions of the pipe used can be adjusted within the FreeCAD [89] files to the dimension of a pipe that is commonly available in the user's region and all other dimensions will adjust accordingly.

Manufacturing

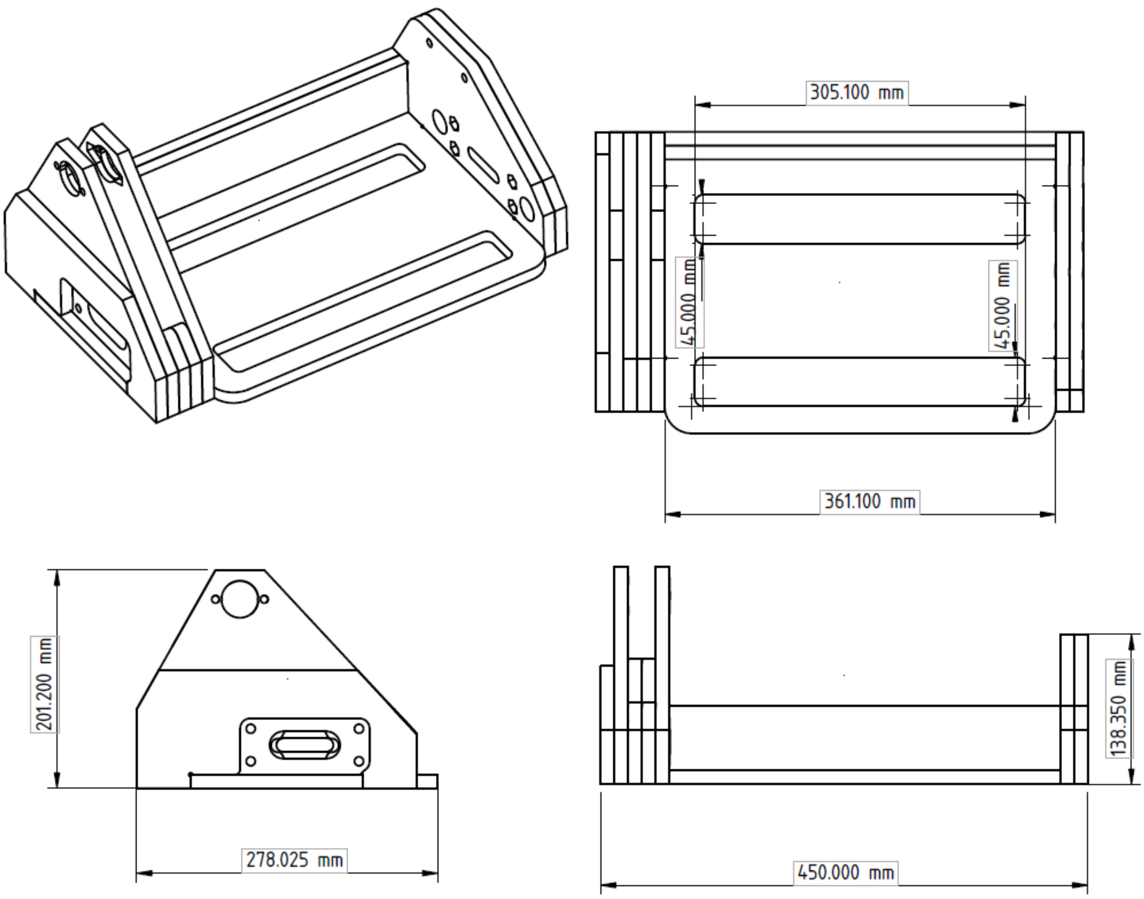
The 3D-printable parts were manufactured on a Lulzbot Taz 6 (FAME 3D, Fargo, ND, USA). Print parameters for all PLA components were as follows: 30% gyroid infill, 4 perimeters, 5 top layers, and 4 bottom layers. TPE parts were printed with 6 perimeters at 100% gyroid infill. To make the plywood parts, a CNC wood router was used. The CNC had a cutting area of 500 × 500 mm, however any dimensionally accurate CNC router with a 450 × 450 mm cutting area could be used. Alternatively, if a CNC router is unavailable, a wood working saw capable of cutting curves in plywood such as a jigsaw or a bandsaw could be used to cut the parts out. The most important dimensions are the position and fit of the holes that secure the metal pipe and the top holes that secure the pillow block flange bearings. While there are several ways to accomplish cutting out the holes with correct dimensions, if not using a CNC, a drill press will provide the best results given that it is capable of drilling perpendicular to the plywood. Once all parts are 3D printed, cut out, or purchased, assembly can begin.

### 2.2. Assembly

Detailed assembly instructions are provided on Appropedia.org [90]. The main assembly steps are summarized here:

1 Building the frame

All plywood components must be cut out prior to beginning assembly of the machine. For gluing together plywood, use wood glue in the areas where two pieces of plywood are in contact only. After they are glued, parts should be pressed together by driving wood screws through them to help clamp the two boards together. Use the conduit passing through specified boards to keep the glued boards lined up with one another. The plywood pieces must be glued together in three subassemblies (chuck end, free end, and back cross-section). These subassemblies can then be placed on the base and secured together using wood glue and screws. The fully assembled frame is shown in Figure 1.




(a)

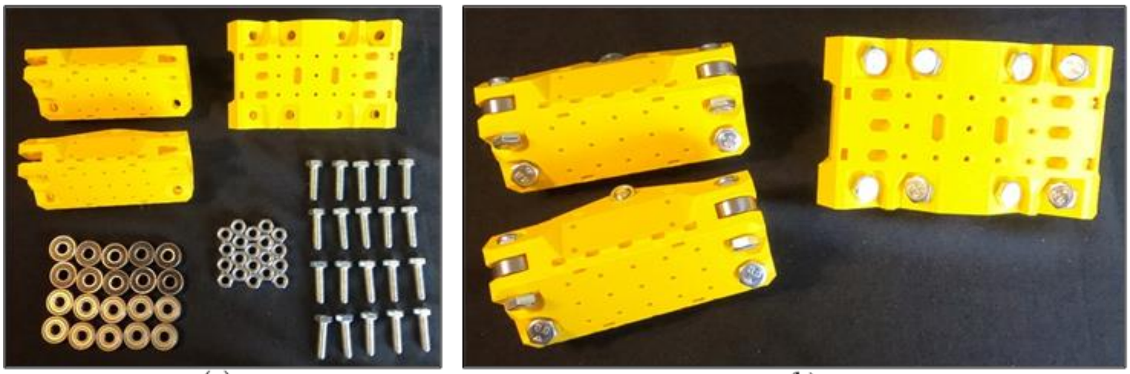
**Figure 1.** *Cont.*

(b)

**Figure 1.** (**a**) CAD with dimensions of plywood frame and (**b**) image of completely assembled frame.

2 Assembling 3D-printed components

a In all three sliders, bolt in the 608ZZ bearing with M8 bolts and a lock nut shown in Figure 2.



(a) (b)

**Figure 2.** (**a**) *X*-axis and *Y*-axis sliders with all the bearings, bolts, and locknuts; (**b**) *X*-axis and *Y*-axis sliders with bearings installed.

b On the *Y*-axis slider, install:

i. Tool quick-release mounting hardware,
ii. Probe mount, and
iii. Threaded rod with the pointed end into the probe mount.

c On the X sliders install:

i. *Y*-axis tube lower mount, and
ii. Threaded rod coupler to connect the two X sliders.

d On the angle grinder install:

i. Required tool mounting hardware which will vary based on what model angle grinder is being used.

e On the free-end support, attach two bearings to the top holes and one to the top clamp with an M8 bolt and lock nut. The top clamp should be mounted on the same M8 bolt that secures the two lower bearings.

f Attach 1 flange pillow block bearing on each threaded rod tension slide, leaving it loose enough to slide the bearing.

g On both pulleys, insert M3 nuts and start M3 × 12 mm bolts into the nuts.

h Using M3 hardware, connect the desired profile to the profile mount.

3 Combining assembled parts

a *X*-axis assembly.

i. Insert *X*-axis tube through the open holes on the end-cap subassembly.

b Push the X sliders onto the tube and insert the tube all the way into the chuck-end assembly until it reaches the backing board C5.

c Install the drill chuck assembly with the desired chuck side pulley mounted onto the shaft of the chuck.

i. Make sure the belt is looped around the chuck shaft.

d Install the threaded rod tension slide on both ends with M8 bolts and M8 lock nuts, as shown in Figure 3.

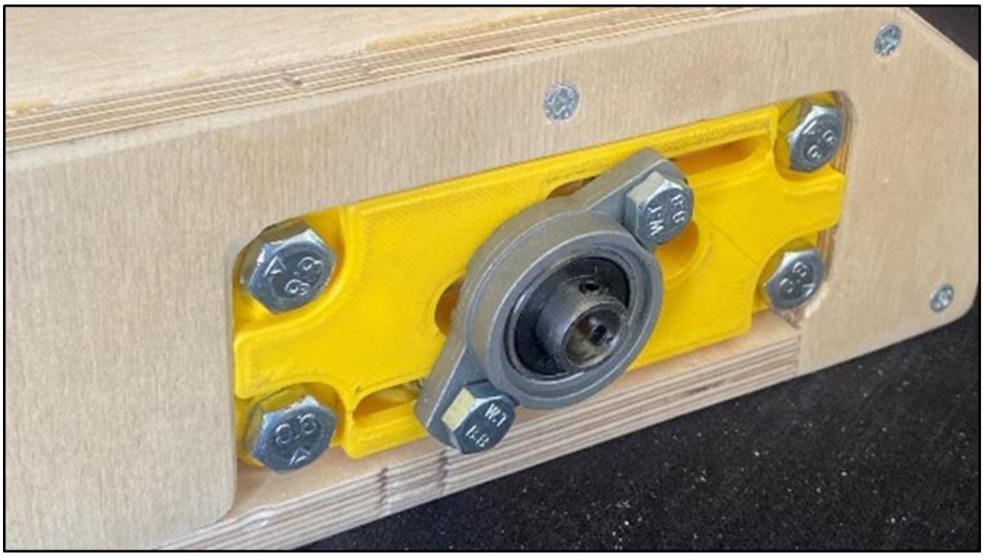


**Figure 3.** Threaded rod tension slide installed onto the chuck end of the plywood frame.

e Threaded rod installation

i. Insert the threaded rod through the free-end side pillow block bearing and move it up to the X slider. Insert a hex nut on each side and a spring in the middle to reduce backlash. Screw the threaded rod onto both nuts. Continue rotating the rod, moving it closer to the front of the chuck assembly. Screw on a pair of hex nuts, lower pulley, and then add another pair of hex nuts. Push the threaded rod through the other pillow block bearing and check that the pulley is lined up with the pulley attached to the chuck. Tighten the nuts on both sides of the pulley and tighten the M3 bolts on the pulley itself to secure it in place. Reinsert the threaded rod through the pillow block bearing and secure a pair of hex nuts on both ends of the threaded rod to help keep the threaded rod from moving. Install the belt on both pulleys, slide the threaded rod equally on both sides, and tighten the pillow block bearings.

f Installing the *Y*-axis subassembly

i. Slide on the Y slider onto the *Y*-axis tubes.
ii. Insert the *Y*-axis tubes and secure with the 3D-printed tube clamp.

g Install the free-end support, leaving it loose enough to be able to adjust it when adding round stock.
h Install angle grinder with appropriate grinding disk onto the Y slider.
i Install the profile mount onto the back cross-section and adjust to align with the cutter disk and the round stock.

4 Assembly is now complete. The completely assembled machine is shown in Figure 4.

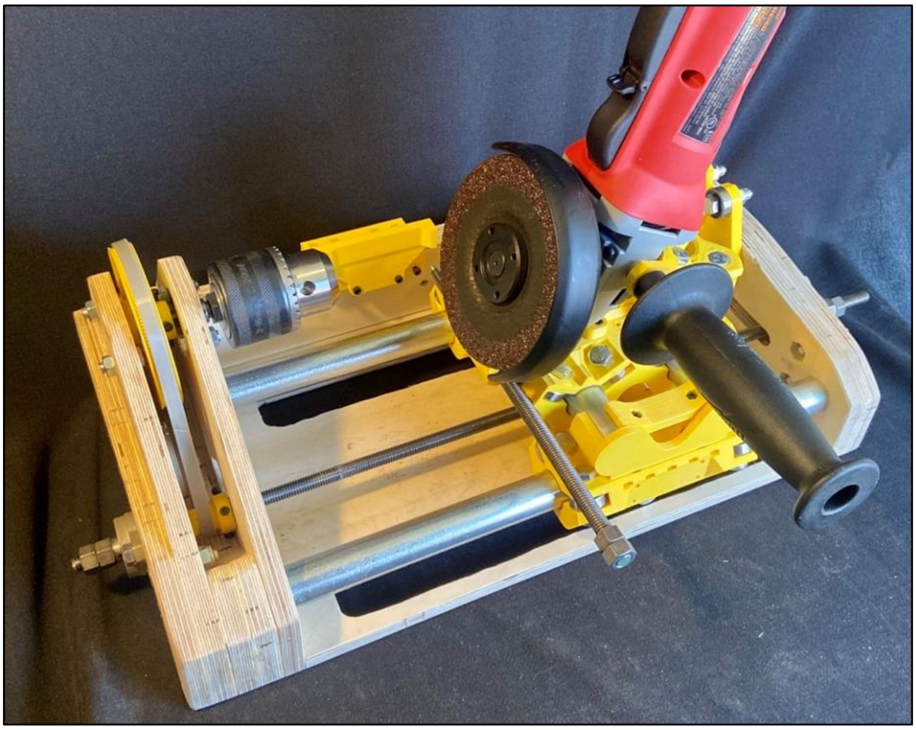


**Figure 4.** Threaded rod tension slide installed onto the chuck end of the plywood frame.

## 2.3. Operation

### 2.3.1. Machine Operation

Operation of the machine can be seen in Video S1 in the Supplementary Materials and is detailed in Appendix B. The basic operation follows five steps:

1. Install desired round stock.
2. Check that a proper abrasive grinding disk is installed on the angle grinder for the material being cut.

    a It is economically advantageous to employ a more heavily used grinding disk for roughing passes and a new disk for finishing passes.

3. To move the tool, rotate the threaded rod. The direction of rotation is dependent on the handedness of the threaded rod used.
    a. Rotation can be achieved by attaching a drill onto the hex nuts at the end of the threaded rod. Alternatively, if a drill is unavailable, a ratchet wrench, or a 3D-printed crank could be used to rotate the threaded rod. While operating by hand is possible, it will take much longer to move the tool along the $X$-axis.
4. For the initial operation cycle, the grinder motion in both axes must be checked to ensure the grinder is able to move freely.
5. Setting the angle grinder to the $Y$-axis position:
    a. Align the angle grinder with the round stock that is installed in the chuck at the starting point.
    b. Move the profile mount to where the starting point on the profile is aligned with the probe.
    c. Move the probe such that it is in contact with the pad to the left of the starting point.
        i. It is important that the profile is designed for the diameter of the round stock. Using a profile designed for 10 mm round stock on 8 mm round stock could result in cutting through the round stock depending on the profile.
    d. Once the probe is set, run the grinder while the machine is off down the length of the round stock to check that it is just contacting the round stock.
    e. At this point, return the grinder to the starting point for the shaping process.
        i. Make a shallow first cut that should only be approximately 0.5 mm in depth.
        ii. Once at the end of the screw, return the grinder back to the start.
            1. The grinder can remain on or off.
        iii. Make several passes, removing approximately 1 mm of material in each pass.
            1. Repeat until the probe is in contact with the profile for the entire pass.
    f. Once the screw has been cut, it is now time to move onto finishing the finishing steps. Finish the screw by sanding down the burrs and polishing.

#### 2.3.2. Machine Performance Requirements

This machine is capable of machining compression screws with similar characteristics as the available micro compression screws on the market [91–93] and allows for optimization of the screw geometry [94,95]. Micro compression screws that are currently on the market have very shallow channel depths rendering them incapable of processing most virgin plastic pellets. Figure 5 shows the purchased screw [93] with virgin PLA plastic pellets, demonstrating how standard pellets have difficulty feeding into extrusion systems using this screw.

This open-source grinding machine can create a more functional screw by allowing the operator to have more control over channel depth, screw diameter, and other parameters relevant to screw optimization including screw length, channel width, and compression ratio.

### *2.4. Validation Tests*

To test the open-source grinder, the following tests were performed:

1. Machine characterization for costs, screw section length cut, diameter rod range, and battery-life test for grinding screws 110 mm in length.
2. Demonstration of screw cutting with variation in (i) channel depth, (ii) screw diameter, (iii) screw length, (iv) change in pitch, (v) abrasive disk thickness, (vi) the handedness of the threaded rod, (vii) and various materials including 1045 steel, 1144 steel, and 416 stainless steel.

**Figure 5.** Image of the purchased micro compression screw with virgin PLA pellets that would typically be used for fused particle fabrication or filament manufacturing. Take note that the channel depth is significantly smaller than the diameter of the pellets.

## 3. Results

### 3.1. Machine Characterization

The fully assembled compression screw manufacturing machine is pictured in Figure 6. The total cost of the machine is approximately $160USD, not including the cutting tool used for machining the compression screws. The machine in its current configuration can cut a screw section up to 110 mm in length. It is also capable of cutting up 4–16 mm diameter round stock. The cutting tool used in this machine is a battery-operated angle grinder [96]. One 18 volt 4.0 AH, 72 Wh battery will last for two complete screws. The machine is designed to be compatible with most 4–1/2″ angle grinders after redesigning the tool mounting bracket and angle brackets for the particular angle grinder being used.

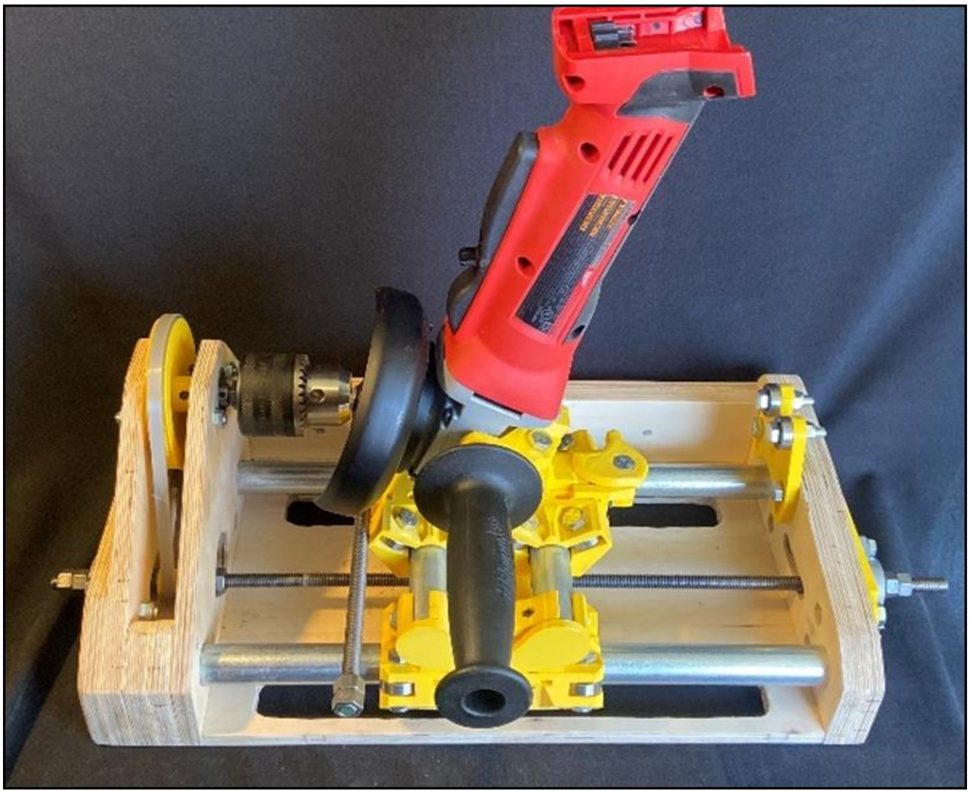


**Figure 6.** The fully assembled compression screw manufacturing machine.

## 3.2. Machined Compression Screws

Several example screws have been manufactured to showcase the different parameters that can be changed by simply changing the handedness of the threaded rod, pulleys, tool mounting angles, and abrasive disk thickness. The diameter of the manufactured screw pictured in Figure 7 is identical to the purchased screw, however it features improved channel depth to allow larger plastic pellets to enter the extruder. The greater feed zone channel depth will also allow a broader range of plastic materials to be used with the manufactured screw.

**Figure 7.** The top screw is the original purchased screw with a channel depth of 1.6 mm. The bottom screw was manufactured with the machine detailed in this report and has a channel depth of 2.5 mm. Both screws have an outer diameter of 8 mm.

While channel depth can be improved in the 8 mm screw as demonstrated in Figure 7, the 8 mm diameter constraint limits the total achievable channel depth. A larger diameter can facilitate a deeper channel depth while reducing torsional shear stress. Given that the common virgin plastics available on the market are intended to be used in larger extrusion systems, an 8 mm diameter screw is simply not large enough for pellets to adequately feed into the system. Increasing the diameter of the screw to 10 mm allows for enough channel depth to feed standard PLA pellets as shown in Figure 8.

**Figure 8.** This screw was manufactured with a 10 mm diameter and a channel depth of 3.8 mm. Virgin PLA pellets fit nicely with these screw dimensions.

The length of the screw offers another area of customization using this machine. In Figure 9, a comparison of the purchased compression screw with a custom-manufactured screw is pictured. The longer screw section increases the length of the feed zone, compression zone, and metering zone. The screw length parameter is limited only by the length of the machine itself and the profile design used.

Using the proposed machine, the pitch and helix of the angle is also customizable. The desired pitch and helix angle can be accomplished by changing out the pulleys for a different tooth count to change the distance traveled by the tool per rotation of the round stock. When changing the pitch, the angle of the tool will also have to be adjusted to match the helix angle for the new pitch as well as the stock diameter. In Figure 10, two 10 mm diameter screws with different pitches are shown. A higher-pitch screw will have a thicker flight width. If the pitch is too low for the abrasive disk thickness, it will pass over the flights of the screw, rendering the screw unusable.

**Figure 9.** Comparison between the purchased screw (top) and a machined screw with an extended length (bottom).

**Figure 10.** Comparison of two screws with a 10 mm diameter and different pitches. The top and bottom screws were manufactured using a 10 and 11.4 mm pitch, respectively.

Another screw variation made with the machine was using a 3.175 mm thickness abrasive wheel, creating a channel width of 4.75 mm compared to the 8 mm channel width created by a 6.35 mm thick abrasive wheel. The comparison of the different abrasive wheel thicknesses is shown in Figure 11.

**Figure 11.** Comparison between a screw using a 3175 mm thick abrasive disk (top) and a 6.35 mm thick abrasive disk (bottom).

The handedness of the threaded rod used is identical to the handedness of the screw being machined. An example of a left-hand threaded screw and a right-hand threaded screw are shown in Figure 12.

**Figure 12.** Comparison of a right-hand threaded screw (top) and a left-hand threaded screw (bottom).

The last variation made utilized a new material, 416 stainless steel. The two stainless steel screws are shown in Figure 13. All other 8 mm screws were manufactured using 1045 steel. The 1144 steel was used for the 10 mm diameter screws.

**Figure 13.** An example of two screws manufactured from 416 stainless steel.

## 4. Discussion

*Machine Limitations*

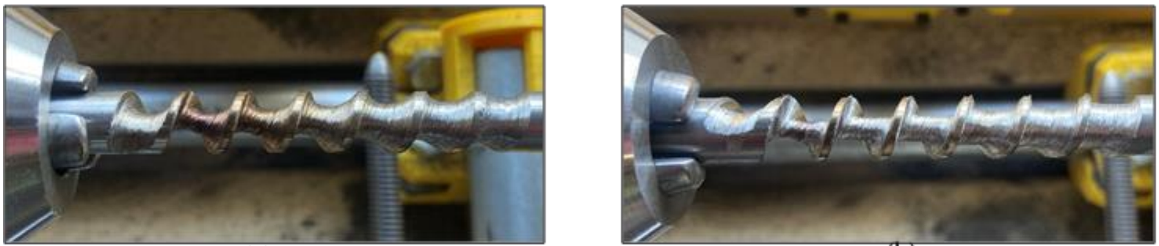
While use of abrasive grinding disks can remove material from the round stock in a controlled manner, the profile of the abrasive wheel changes with extensive use. As material is removed, the wheel diameter is reduced over time which can cause the channel depth to be shallower than desired unless the probe is adjusted before the final pass to correct this issue. Another problem with the abrasive wheels is a changing profile from a squared to rounded edge over time as shown in Figure 14.

A potential countermeasure for this issue is to use a new abrasive wheel for a final pass over the part. In Figure 15, before and after images of a screw that has had a finishing pass are shown.

In addition, the use of common abrasive grinding disks available at most hardware stores for angle grinders is only recommended to cut steel and stainless steel. Discs specifically designed for use with soft metals may be found at specialty suppliers.

The maximum diameter stock size constrained to under 16 mm by the purchased drill chuck presents another potential limitation of this machine. For most micro compression screw designs, a 16 mm diameter is sufficient and will not present an issue. If for some reason the manufacturer desired larger-diameter round stock, a round stock with a diameter greater than 16 mm would not be able to fit in the current drill chuck specified in the BOM.

**Figure 14.** Comparison of a disk after 10 screws (bottom) and an unused disk (top).



(a) (b)

**Figure 15.** (**a**) Compression screw ground using a worn-down abrasive disk. (**b**) Compression screw with a finishing pass using a new abrasive disk.

Lastly, in its current state, the machine relies on mechanical gearing to determine the screw parameters. Experimentation with different screw parameters while necessary can be a bit tedious, especially as adjusting screw pitch requires removal of the chuck to change pulleys and undoing the chuck side of the threaded rod to remove the pulley. Future work is needed to make this process less time consuming. Compression screws could be manufactured using a CNC mill with a fourth axis, or a CNC lathe. Industrial extrusion screws are manufactured using a cylindrical grinding machine [97]. The machine developed in this work is classified as an outside diameter cylindrical grinding machine [98].

In the future, this invention can be improved in several ways. First, this machine could be improved to make operation of the machine safer, easier, and faster to use. One aspect that would improve the design would be to consider machining dynamics [99,100]. The current version of the machine never had a problem with natural frequencies or performance under harmonic loadings. With particular selections of materials and geometries, this may not be the case and a detailed mode analysis could determine the limits of this design. Core design elements of the original design can then be used to create a computer numerically controlled (CNC) operated version of the machine. This version of the machine could be automated and thus networked so that it could be operated and supported from external programmers and users. A CNC version of the machine will allow for handsfree operation and faster experimentation with different screw parameters and rapid prototyping. In addition to DRAM, this machine could be used in devolved manufacturing [101,102]. Finally, applying what has been learned on the micro compression screw manufacturing machine, a dedicated machine for creating screws for filament extruders and industrial-sized pellet 3D printers will be created.

This grinding device was able to successfully manufacture custom extrusion screws, which radically reduce the cost of one of the core components of desktop-sized open-source FPF 3D printers [85]. This ability will provide the maker community with access to low-cost screws, thereby benefiting the circular economy based on distributed recycling and additive manufacturing [43–46], regardless of whether it is home-based manufacturing or a more centralized form of distributed manufacturing (e.g., community based) [103].

## 5. Conclusions

This study provided the details of an invention for a low-cost, easily replicable open-source grinding machine for compression screw manufacturing. The designs followed the RepRap methodology, as many of the components of this grinding machine can be fabricated using FPF/FGF, which would be enabled by the screws that the system manufactures. This grinding machine for compression screw manufacturing can be made from <$155 in parts and the cost of a cordless cut-off grinder (~$130). The new invention is demonstrated to be able to cut custom screws with variable (i) channel depths, (ii) screw diameters, (iii) screw lengths, (iv) pitches, (v) abrasive disk thicknesses, (vi) the handedness of the threaded rod, (vii) and three types of steel, 1045 steel, 1144 steel, and 416 stainless steel. The results show that the device is more than capable of replicating commercial screws as well as providing makers with a much greater flexibility to make custom screws. This ability added to the DRAM toolchain by enabling makerspaces, fab labs, companies and universities to fabricate compression screws rapidly for approximately the cost of the bar stock, which assists the goals of the circular economy based on distributed recycling and additive manufacturing.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2411-5134/5/3/26/s1, Video S1: How to Use the Open-Source Grinding Machine for Compression Screw Manufacturing.

**Author Contributions:** Conceptualization, J.F. and J.M.P.; methodology, J.F. and J.M.P.; validation, J.F.; formal analysis, J.F. and J.M.P.; investigation, J.F.; resources, J.M.P.; data curation, J.F.; writing—original draft preparation, J.F. and J.M.P.; writing—review and editing, J.F. and J.M.P.; visualization, J.F.; supervision, J.M.P.; funding acquisition, J.M.P. All authors have read and agreed to the published version of the manuscript.

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

## Appendix A. Manufactured Components

**Table A1.** Manufactured Components for the Open-Source Grinding Machine for Compression Screw Manufacturing.

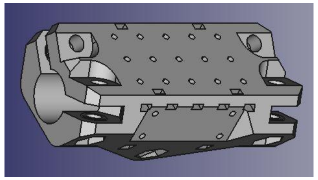
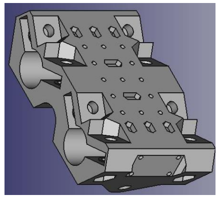
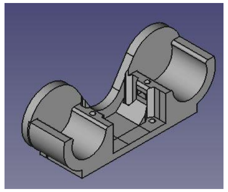
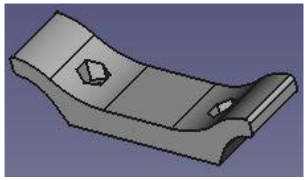
| Name | | Quantity | Description | Mater-ial | Manufacturing Methods/Settings |
|---|---|---|---|---|---|
| *X*-Axis Slider |  | 2 | Used for linear motion platform for the *X*-axis | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| *Y*-Axis Slider |  | 1 | Used for linear motion platform for the *Y*-axis | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm Nozzle<br>• 5 top, 4 bottom layers |
| *Y*-axis Tube Lower Mount |  | 2 | Mounting the pipes used for the *Y*-axis | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| *Y*-Axis Tube Top Clamp |  | 2 | Securing the *Y*-axis pipes | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |

**Table A1.** *Cont.*

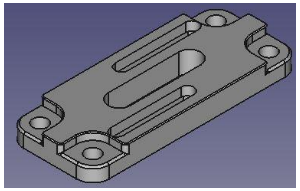
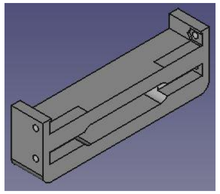
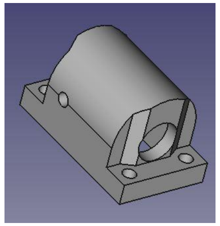
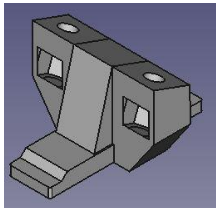
| Name | | Quantity | Description | Mater-ial | Manufacturing Methods/Settings |
|---|---|---|---|---|---|
| Threaded Rod Tension Slide |  | 2 | Mounting the pillow block flange bearings that hold the threaded rod | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Threaded Rod Coupler |  | 2 | Used to connect the *X*-axis sliders and holds the two nuts and spring that are installed on the threaded rod | PLA | 3D Printed<br>• 40% gyroid infill<br>• No supports<br>• 6 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Probe Mount |  | 1 | Holds threaded rod with a pointed end that is used to follow the profile part | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Grinder Mount Angle |  | 1 | Positions the angle grinder to match the helix angle of the screw being machined. Attached to *Y*-axis slider with the quick-release lockdown | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |

**Table A1.** *Cont.*

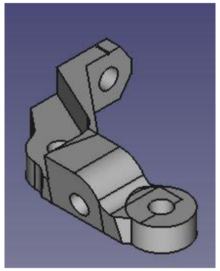
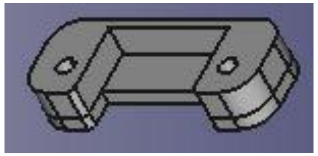
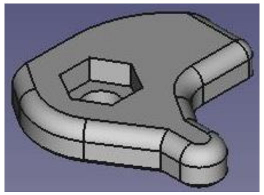
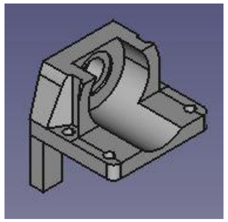
| Name | | Quantity | Description | Mater-ial | Manufacturing Methods/Settings |
| --- | --- | --- | --- | --- | --- |
| M18 Bracket |  | 1 | This bracket is mounted onto the Milwaukee 2680 angle grinder. Other models might require a different bracket to be designed | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Quick-Release Bridge Clamp |  | 1 | Part of the quick-release lockdown system to secure the angle grinder mount | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Quick-Release Lockdown Lever |  | 1 | Lever to secure the angle grinder tool mount | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Lock-Side Grinder Mount |  | 1 | Bracket that holds the quick-release lockdown lever | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |

**Table A1.** *Cont.*

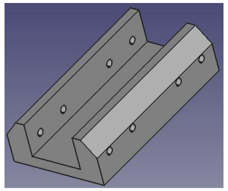
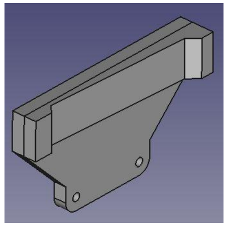
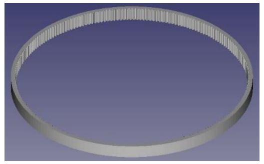
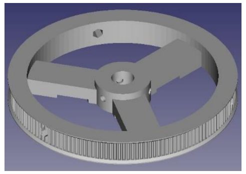
| Name | | Quantity | Description | Mater-ial | Manufacturing Methods/Settings |
|---|---|---|---|---|---|
| Profile Mount |  | 1 | Mounts onto cross-brace to secure two different profiles for machining | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Profile |  | 1 * | The probe on the *Y*-axis slider moves across the face of the profile to control the channel depth of the screw during grinding | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Belt |  | 1 * | Belt to connect the chuck and threaded rod pulleys | Nijatek Ninjaflex 85 A | 3D Printed<br>• 100% gyroid infill<br>• No supports<br>• 8 perimeters<br>• 0.4 mm nozzle<br>• 4 top, 4 bottom layers |
| Chuck Pulley |  | 1 * | Mounted on the chuck shaft that controls the pitch of the screw | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |

**Table A1.** *Cont.*

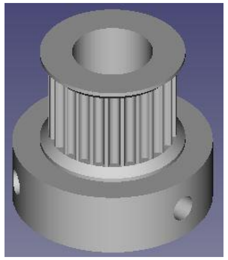
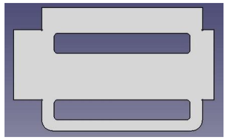
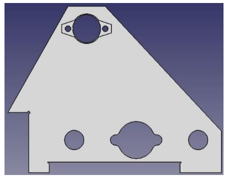
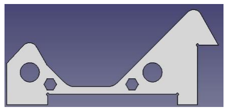
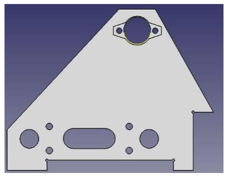
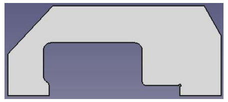
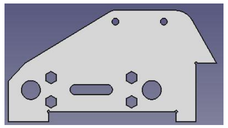
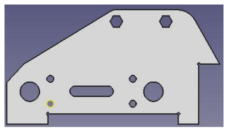
| Name | | Quantity | Description | Mater-ial | Manufacturing Methods/Settings |
|---|---|---|---|---|---|
| Threaded Rod Pulley |  | 1 * | Mounted on the threaded rod to control the pitch of the screw | PLA | 3D Printed<br>• 30% gyroid infill<br>• No supports<br>• 4 perimeters<br>• 0.5 mm nozzle<br>• 5 top, 4 bottom layers |
| Base |  | 1 | Base of the plywood frame | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>1. CNC router<br>2. Jigsaw, router, and a drill<br>3. Bandsaw, router, and a drill |
| C1 |  | 1 | Chuck-end component | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>4. CNC router<br>5. Jigsaw, router, and a drill<br>Bandsaw, router, and a drill |
| C2 and C3 |  | 1 | Chuck-end component | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>6. CNC router<br>7. Jigsaw, router, and a drill<br>Bandsaw, router, and a drill |
| C4 |  | 1 | Chuck-end component | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>8. CNC router<br>9. Jigsaw, router, and a drill<br>Bandsaw, router, and a drill |

**Table A1.** *Cont.*

| Name | | Quantity | Description | Mater-ial | Manufacturing Methods/Settings |
| --- | --- | --- | --- | --- | --- |
| C5 |  | 1 | Chuck-end component | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>10. CNC router<br>11. Jigsaw, router, and a drill<br>Bandsaw, router, and a drill |
| Cross-Brace |  | 1 | Connects the chuck-end subassembly and the free-end subassembly | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>12. CNC router<br>13. Jigsaw, router, and a drill<br>Bandsaw, router, and a drill |
| F1 |  | 1 | Free-end component | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>14. CNC router<br>15. Jigsaw, router, and a drill<br>Bandsaw, router, and a drill |
| F2 |  | 1 | Free-end component | $\frac{1}{2}$″ Baltic birch plywood | Multiple methods<br>16. CNC router<br>17. Jigsaw, router, and a drill<br>Bandsaw, router, and a drill |

## Appendix B. Operation Details of Open-Source Grinder

When creating screws from drawings or CAD models (as shown in Figure A1), the following are several best practices to follow during the machining process. First, take many shallow passes with the tool constantly moving while in contact with the stock. Second, keep in mind that the abrasive disk controls the profile of the channel. It is important to use a new disk with square, non-rounded corners for finishing passes if the desired channel profile is flat. Lastly, continue making passes until the grinder is no longer removing material and the sparks generated by the machine slow considerably. For a clear and complete understanding of machine operating practices and principles, please consider watching the video guide (Video S1) provided in the Supplementary Materials. The video guide highlights machine operation from start to finish including tasks such as changing out the pulleys, mounting the angle grinder, and switching profiles. Customization of the pulleys and grinder mount is easily achievable by changing values within a spreadsheet inside the main design FreeCAD file. Updating the desired pitch and stock diameter will adjust the grinder mount and output the values to be entered into the OpenSCAD pulley file. The profile is created in FreeCAD and must be designed based on the desired compression ratio, channel depth, and overall length of the screw. While profiles can be used for various pitch screws, they should not be interchanged with different diameter stock materials. As this is a manually controlled machine, creating several test pieces and conducting practice runs as needed will likely be helpful to new users to better understand how the machine performs throughout the screw manufacturing process. The process is summarized in Table A2.

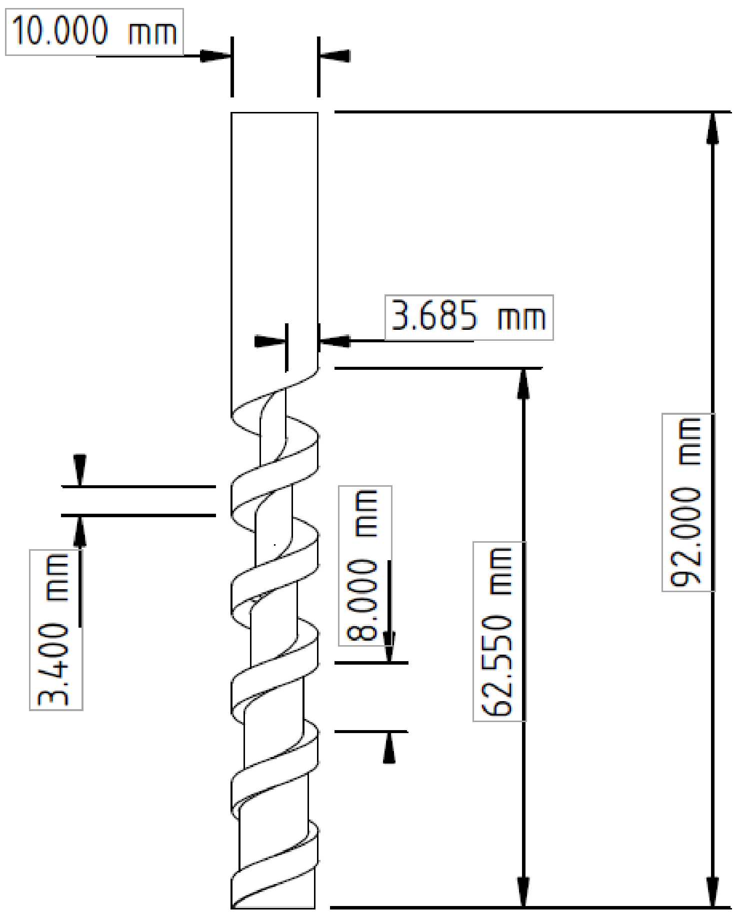



**Figure A1.** Screw CAD with dimensions.

**Table A2.** Process sheet for fabricating a screw with the open-source grinding machine.

| Task Number | Name of Operation | Description of Task | Estimated Time (minutes) | Notes |
|---|---|---|---|---|
| 1 | Loading stock | Installing stock into chuck and adjusting supports | 5 | Ensure the stock is parallel to the X-axis of the machine |
| 2 | Grinder alignment | Setting the starting depth of the grinder and positioning the profile | 2 | If performing a finishing pass, have the finishing pass disk installed |
| 3 | Roughing disk installation | Install the disk to be used for roughing passes | 1 | |
| 4 | Roughing pass | Start making passes with the grinder removing the bulk of the material | 2 | Make sure not to force the angle grinder hard into the stock, as it may bend the stock material. If the stock is starting to change color, the feed rate is too fast |
| 5 | Finishing disk installation | Install the disk to be used for finishing passes | 1 | This disk needs to have minimum wear |
| 6 | Finishing pass | Removing excess stock not reached by the roughing disk | 1 | Machine screw until the desired geometry is made |
| 7 | Stock removal | Removing screw and excess stock from the machine | 2 | |
| 8 | Cutting screw from stock | Cutting off the screw from the stock material | $< 1$ | Angle grinder with a thin cut-off disk to be used |
| 9 | Screw finishing | Removal of burrs left from the grinding process and polishing the screw | 10+ | Methods for this section will vary based on tools available |

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