

Additive Manufacturing of a set of Herringbone Gears Assembly

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Research Article

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Abstract

Herringbone gears are frequently used in power transmission systems due to their ability to reduce axial thrust and provide smooth, quiet operation. However, producing them conventionally is costly and challenging due to their intricate double-helical structure. This work investigates the feasibility of fabricating polymeric herringbone gears for low-load applications, such as external gear pumps, by additive manufacturing (AM). We utilized SolidWorks for parametric modeling, Simplify3D for toolpath planning, and fused filament fabrication (FFF) for part production. Two identical herringbone gears, two shafts, and a supporting bracket were fabricated and assembled to create a functional prototype. The initial prototypes including fine teeth and dual-shaft hubs proved ineffective due to excessive support requirements and insufficient strength. A novel design featuring fewer, thicker teeth and a streamlined hub shape significantly enhanced printing and mechanical performance. The findings indicate that FFF is applicable for the fabrication of functioning polymeric herringbone gears for demonstration-scale purposes. Nonetheless, they also indicate that there are issues with feature resolution, build duration, and mechanical integrity. Selective laser sintering (SLS) with nylon has been identified as a superior technique for fabricating geometrically complex and mechanically robust herringbone gears. These results underscore the significance of additive manufacturing in the fabrication of intricate gear geometries and highlight critical design and process considerations for polymer-based power transmission components.

Introduction

Gears are essential elements of power transmission systems, with their design and production process influencing performance, efficiency, and cost. Spur gears are the most commonly manufactured due to their simplicity and ease of production using injection molding or traditional machining methods. Nevertheless, due to their straight teeth engaging abruptly throughout the full width of the face, spur gears are susceptible to vibration and noise. Helical gears mitigate this limitation by utilizing inclined teeth that provide progressive engagement, leading to smoother and quieter operation [1]. A drawback of helical gears is the production of axial thrust, which escalates with the helix angle and may impair performance when elevated angles are necessary.

Herringbone gears, formed by combining right-hand and left-hand helices, overcome this limitation by balancing axial forces, thereby eliminating net thrust. This configuration allows quiet, efficient operation even under higher torque conditions. Consequently, herringbone gears are used in demanding applications such as steam turbines, ship propulsion gearboxes, parallel-axis drives, and hydraulic pumps. Their main drawback lies in manufacturing complexity: double-helical geometries cannot be produced by conventional gear hobbing machines or standard CNC processes without specialized equipment, making them costly to fabricate [2].

Additive manufacturing (AM) provides an promising solution by facilitating the direct fabrication of intricate geometries [3], such as herringbone gears, without the limitations imposed by conventional tooling. Moreover, polymer-based gears manufactured using additive manufacturing are lighter, quieter, and more cost-effective than metal alternatives, making them ideal for low-load applications. Despite possessing low tensile strength and durability, polymers are suitable for lightweight pumps and low-duty transmission systems. Herringbone gears in external gear pumps are particularly advantageous due to their geometry, which offers less pulsation and enhanced pumping efficiency compared to spur or helical gears.

Among the various AM technologies, fused filament fabrication (FFF) is the most widely adopted due to its cost-effectiveness, accessibility, and material versatility [4, 5]. In FFF, thermoplastic filaments such as PLA, ABS, PETG, and engineering-grade polymers are extruded layer by layer to form three-dimensional parts. Its ability to produce

functional prototypes, customized components, and geometrically complex structures has driven widespread industrial adoption. The automotive and aerospace industries leverage FFF for lightweight structural parts, tooling, and rapid prototyping [6]; the marine sector employs it for custom fixtures and polymer-based housings [7]; and the medical field utilizes it for patient-specific models, implants, and surgical guides. This broad applicability underscores the relevance of FFF for producing polymer gears with intricate geometries, such as herringbone gears, for functional low-load assemblies.

The aim of this project is to design and manufacture a functional herringbone gear assembly utilizing additive manufacturing. Two identical polymeric herringbone gears, two shafts, and a supporting bracket were designed and fabricated using Fused Filament Fabrication (FFF). The constructed prototype illustrates the viability of employing 3D-printed plastic gears inside a streamlined external gear pump design and underscores the potential and obstacles associated with utilizing additive manufacturing in the creation of intricate gear geometries.

Additive Manufacturing Process Overview

Modern manufacturing has progressively transitioned from mass production to customization and specific client requirements, hence generating potential for additive manufacturing (AM). Additive manufacturing is revolutionizing the industry by managing intricate geometrical designs, minimizing tooling needs, and facilitating swift design iterations. In additive manufacturing (AM), items are fabricated layer by layer directly from a computer-aided design (CAD) model, enabling the production of components that are otherwise unfeasible or uneconomical to create using subtractive techniques. The most prominent additive manufacturing technologies are vat photopolymerization, powder bed fusion, material extrusion, material jetting, binder jetting, sheet lamination, and directed energy deposition [8]. Additive manufacturing accommodates a wide array of materials, encompassing polymers, composites, metals, ceramics, as well as paper laminates and waxes. In contrast to CNC machining, additive manufacturing provides unique benefits by removing the need for tooling and facilitating the creation of intricate interior features, hollow structures, and integrated assemblies through the transformation of 3D blueprints into layered 2D slices.

This project utilized material extrusion as the principal additive manufacturing technique, specifically using fused filament fabrication (FFF), often referred to as fused deposition modeling (FDM). The process commences with the design of the gear assembly in CAD software, followed by exporting the model to slicing software to produce g-code, and subsequently uploading the file to the printer. FFF systems comprise three primary components: the filament spool, the build platform, and the extrusion head. A thermoplastic filament is introduced into the system, heated in the extrusion nozzle beyond its melting point, and extruded in a semi-liquid form along specified toolpaths. The extrusion head traverses the x-y plane as the build platform descends (or the head ascends) progressively in the z-direction following the completion of each layer. The deposited material cools and hardens, adhering to the preceding layer until the component is entirely constructed.

FFF is the most straightforward, cost-effective, and prevalent additive manufacturing technology; nonetheless, it possesses certain drawbacks. The size of the nozzle directly influences both build quality and duration: larger nozzles (e.g., 0.8 mm) enhance throughput but diminish surface resolution, whereas smaller nozzles (e.g., 0.35 mm) yield finer details at the cost of print speed. Print resolution is limited by layer thickness, generally not less than 0.1 mm, hence restricting sharp edge definition. Components frequently demonstrate anisotropy attributable to the raster pattern, exhibiting diminished strength in the z-direction relative to the x-y plane. Filament expansion

during extrusion may impact dimensional accuracy, complicating the management of tolerances. Warping and layer delamination are prevalent flaws that necessitate optimal printing parameters and environmental regulation.

A diverse array of thermoplastics is utilized in Fused Filament Fabrication (FFF), encompassing PLA, ABS, nylon, PETG, and TPU. Acrylonitrile butadiene styrene (ABS) was chosen for this project because of its advantageous combination of rigidity, toughness, and impact resistance. ABS is a terpolymer in which styrene imparts processability and rigidity, acrylonitrile offers chemical resistance and thermal stability, and butadiene improves toughness. These attributes render ABS particularly suitable for gears, which must endure constant rotation, meshing impact, and mild loads. Nonetheless, ABS is susceptible to shrinkage upon cooling, leading to warping; hence, a sealed build chamber was employed to ensure a uniform temperature throughout the fabrication process. Further benefits of ABS encompass affordability, extensive availability, ease of machining, and a polished surface quality [9]. PLA, meanwhile, was excluded due to its inferior impact strength, rendering it unsuitable for dynamic gear applications.

COMPONENT (OR ASSEMBLY) DESIGN

The design of the two herringbone gears (helix direction – righthand and lefthand), two identical shafts, and the bracket were carried out in SolidWorks 2019. Both the gears have a module of 10 mm, number of teeth of 12, a helix angle of 30° , a pressure angle of 20° , a face width of 80 mm (40 mm each), hub style A (meaning the gear has shaft attached to it on one side only), a nominal shaft diameter of 30 mm, bore length of 125 mm, and a keyway of rectangular shape. The only difference between the two gears is the helix direction (righthand and lefthand). To make sure that the gears mesh, the module is similar for both. Residual stress can cause defects like cracking. To alleviate residual stress, fillets were designed on the teeth of the gears. No topology optimization was carried out for material reduction in gear because the idea behind manufacturing these gears is that they can be used in a gear pump. The gears in a gear pump need to have their full volume so that no water passes through the gears, Water should only pass between the teeth gap.

The bracket was designed with two holes in it so that the designed shafts can pass through these holes. The inside hole of each gear passes through the outside of each shaft. Each gear is designed with a keyway and each shaft is designed with a key. This arrangement is made so that if one shaft is rotated with an external force, then automatically the two gears and the other shaft rotate at the same speed. The bracket is always stationary which carries the whole arrangement.

In addition, a simulation was run in SolidWorks 2019 to see if the designed gear can sustain the load. For simplicity, only the driving gear was considered during the simulation (noted that both gears are identically designed). Teeth are the main vulnerable area while any gear is operating. The teeth are expected to be loaded with two major forces in this case. One such force is the force experienced by the tooth of one gear due to its impact from the tooth of another gear (F_1). The other force is the force experienced on teeth due to the moving liquid in the pump due to the applied torque (F_2). The force, F_1 is developed normal to the contacting surfaces between the mating gears and is the vector summation of three components: tangential force (F_t), radial force (F_r), and axial force (F_a). F_1 is distributed along the contact line that moves with the rotation of the gear.

The applied torque (T) is assumed as 1 N-m. Pitch circle diameter, module, number of teeth, pressure angle, and helix angle are denoted by d , m , n , α , and β respectively. F_t is tangent to the pitch circle in the transverse plane.

$$Ft = \frac{2T}{d}$$

$$Ft = \frac{2T}{mn}$$

$$Ft = \frac{(2)(1)}{(0.01)(12)}$$

$$Ft = 16.67$$

$$Fr = Ft \cdot \tan\alpha$$

$$Fr = 16.67 \cdot \tan 20$$

$$Fr = 6.07 \text{ N}$$

$$Fa = Ft \cdot \tan\beta$$

$$Fr = 16.67 \cdot \tan 30$$

$$Fr = 9.62 \text{ N}$$

$$Fr = \sqrt{Ft^2 + Fr^2 + Fa^2}$$

$$F1 = 20.18 \text{ N}$$

F2 is taken as 138 N from a study [10]. While in operation, all the teeth of the gear will experience F2, however, the mating tooth will alone experience F2 plus F1. Hence the mating tooth will experience a total force of 158.18 N. For simplicity, the simulation is carried out such that all teeth will experience a load of 158.18 N. Under the simulation, at first material was applied which is ABS. The next step was loading. Fixed geometry was applied at the inside part of the gear hole (bore). And normal force of 158 N was applied to each tooth (in total 12 teeth i.e., 24 faces). Afterward, mesh was created using blended curvature mesh. Finally, the simulation was run. The result shows no deformation at any position of the gear. The Von Misses stress values are lower than the yield strength of the material. A high factor of safety is obtained as well.

BUILD PREPARATION

The STL format was created from the CAD model. An STL file uses a collection of connected triangles to define a 3D object's surface geometry. It is also called Standard Triangle Language. The left gear, the right gear, the shaft, and the bracket contain 18650, 17548, 316, and 2084 triangles respectively. The resolution increases with the number of triangles. The shaft and bracket are simple in design and lack any elaborate features, which is why there are fewer triangles on them. The gears have more triangles since their design is more complicated comparatively.

The STL file was then imported into a slicing software called Simplify3D. Then it was time to choose the appropriate process parameter. All the parts were printed with 0.2 mm layer thickness, 40% infill density, 60°C build platform temperature, and 230°C extruder temperature. The printing process speeds by increasing layer thickness, but resolution and part quality suffer. The layer height should, as a general rule, be between 25% and 75% of the nozzle diameter for strong layer-to-layer bonding. The nozzle has a 0.4 mm diameter; hence a layer thickness of 0.2 mm was chosen. Higher infill density increases part strength but also increases print time, material usage, and part

weight. 40% infill density was considered optimal to have enough part strength making it lightweight as well. The platform and extruder temperature were selected as per recommendation for ABS.

Thermal distortion or warping can result from an improper temperature. To ensure the part's maximal strength, the print orientation was in the XY plane. Supports were generated automatically.

Printing the shaft required some attention because of its circularity. At first, the shaft was attempted to print on its side (horizontally) to make sure the part is very strong. But the circularity was very poor with a lot of stair-stepping effect. In fact, it was a failed print. Next, the shaft was printed vertically as shown in the figure. A nice circular shaft was obtained and the strength was enough that it did not break across the layer lines. For printing the shaft, manual support was generated just below the key of the shaft. It is also seen that instead of two shafts, four shafts were printed. The hole of each gear or each hole of the bracket is designed with a diameter of 30 mm. However, the shaft diameter is kept slightly smaller than 30 mm to keep tolerance due to the fact that material extrusion-based technology can result in size variation. Two shafts were designed with 29 mm diameter and the other two shafts were designed with 29.5 mm diameter to see which dimension works. In the end, it was seen that shafts with 29 mm in diameter fitted well into the gear hole and the bracket hole and could be rotated at will.

BUILD EXECUTION AND POST-PROCESSING

The printer used for the build was Flashforge Creator Pro which is based on the FDM process. Each gear is double helical, one helix has 12 teeth and the opposite helix has 12 teeth likewise. And fillets were designed to each tooth, meaning to 24 faces. As far as the design is concerned, there is a gap between the fillet of one tooth to the fillet of its opposite tooth. Not only each fillet was printed nicely but each gap between the fillet was captured to perfection. Each tooth of each gear was also printed very well. The small support structures attached to the printed shafts and the bracket were removed easily by hand. However, the circular support that was attached to the gear (on the opposite side of the nominal shaft attached to the gear) required additional attention to be removed. Initially, the idea was to heat the gear in the oven but this might melt the gear. Instead, this strongly attached support was removed with pliers very gradually.

The print was very good overall for all the parts. This was also demonstrated by making the assembly. The bracket was allowed to sit horizontally on a table. As per the design and the intention, each shaft could fittingly pass through each hole of the bracket and likewise, each gear hole (bore) could fittingly pass through each shaft. The functional purpose was achieved as if one part (left helix gear, right helix gear, one shaft or other shaft) rotates, the other three parts also rotate automatically. To be noted that, the gears and the shafts were printed in MAE Design Innovation Lab. However, to save time, the bracket was printed in FabLab.

COST COMPARISON

The total cost is considered to have four components, namely, purchase cost, machine operation cost (utility cost and rest cost), material cost, and labor cost.

Table 1
General assumptions for cost calculation of all parts

Category	Value	Unit
Printer price	400	USD
Uptime	95	%
Hours in a day	24	hours
Days in a year	365	days
Life of the printer	10	years
Electricity rate	14.18	cents/kWh
Average monthly rate for commercial space in Texas	1000	USD/month
Support factor, K_s	1.5	–
Recyclability factor, K_f	1	–
Material density, ρ	1.05	g/cm ³
Cost of material per unit mass (ABS filament)	24	USD/kg
Labor rate	100	USD/hour

Table 2
Variables for cost calculation of gears

Category	Value	Unit
Build time	15.5	hours
Power output	600	watt
Number of parts, N (two gears)	2	–
Volume (each gear)	584	cm ³
Setup time including post-processing	1	hour

For gears, Purchase cost = \$0.07

Operational cost = \$22.847 [Utility cost and rent cost are \$1.32 and \$21.528 resp.]

Material cost = \$44.15

Labor cost = \$100

Therefore, total cost = \$167.07

Table 3
Variables for cost calculation of shafts

Category	Value	Unit
Build time	1.75	hours
Power output	50	watt
Number of parts, N (two shafts)	2	–
Volume (each shaft)	62.5	cm ³
Setup time including post-processing	0.5	hour
For shafts, Purchase cost = \$0.01		

Operational cost = \$2.443 [Utility cost and rent cost are \$0.01 and \$2.431 respectively]

Material cost = \$4.73

Labor cost = \$50

Therefore, total cost = \$57.18

Table 4
Variables for cost calculation of bracket

Category	Value	Unit
Build time	1	hour
Power output	50	watt
Number of parts, N	1	–
Volume	142.83	cm ³
Setup time including post-processing	0.5	hour

For bracket, Purchase cost = \$0

Operational cost = \$1.396 [Utility cost and rent cost are \$0.01 and \$1.389 resp.]

Material cost = \$5.4

Labor cost = \$50

Therefore, total cost = \$56.80

It is found that the cost of producing the two herringbone gears is \$167.07 by AM process. Thus, the cost of producing one herringbone gear is \$83.54 by AM process. And the cost of producing one such same-designed herringbone gear by conventional manufacturing process is \$214. Thus, AM process costs 60.96% less than conventional manufacturing process. Also, to be noted that, if steel is used instead of plastic by conventional manufacturing process to produce gear, the price will be even higher.

Future Research Directions

While this study demonstrated the feasibility of using polymeric herringbone gears fabricated by FFF for low-load external gear pump applications, several opportunities remain for future research. Recent work has shown that enhanced FFF processes with localized in-situ heating can substantially improve interlayer bonding, geometric accuracy, and flexural strength of thin-walled structures [11]. Incorporating such thermal enhancement strategies could enable the reliable printing of finer gear teeth and taller, more load-bearing geometries. In parallel, machine learning and large language models (LLMs) have emerged as powerful tools for optimizing FFF process parameters and predicting mechanical strength, offering rapid adaptation even with limited experimental datasets [12], [13]. These approaches may allow automated tuning of gear-printing parameters to achieve desired performance with reduced trial-and-error. Moreover, hybrid CFD–ML frameworks in marine engineering have demonstrated the potential of surrogate modeling to accelerate design optimization [14], which could be adapted to gear pump design for predicting flow resistance and efficiency. Collectively, these directions point toward a future where polymeric herringbone gears are manufactured with improved mechanical properties, predictive design integration, and AI-driven process control, thereby extending their application space beyond simple prototypes.

Conclusion

This project demonstrated the feasibility of designing and fabricating functional herringbone gears using fused filament fabrication (FFF) for low-load applications such as external gear pumps. Compared with conventional metal gears, polymer gears provide advantages of reduced noise, lower weight, and ease of manufacture. While spur gears are readily produced through conventional methods, the geometric complexity of herringbone gears makes them well suited for additive manufacturing. In this work, two identical polymer gears, shafts, and a supporting bracket were successfully modeled, 3D-printed, and assembled, highlighting both the potential and challenges of extrusion-based AM for gear applications.

The project offered broad learning outcomes: developing parametric CAD designs in SolidWorks, mastering slicing and printer operation, applying simulation and cost estimation, and deepening understanding of gear mechanics. Limitations were also identified. The initial fine-toothed, dual-shaft gear design failed due to excessive support structures and geometric fragility, while the revised coarse-tooth, single-shaft design improved printability and strength. Furthermore, long build times necessitated part scaling, and extrusion-based printing-imposed restrictions on feature resolution and interlayer strength. Alternative processes such as selective laser sintering (SLS) with nylon are expected to overcome these limitations by enabling support-free fabrication and improved mechanical properties.

Looking forward, recent advances suggest promising directions to enhance this work. In-process annealing and localized heating can improve interlayer bonding and structural integrity of FFF parts, enabling the manufacture of finer gear teeth. Machine learning frameworks, including those leveraging large language models, offer opportunities for process parameter optimization and predictive modeling of gear performance. Finally, hybrid computational fluid dynamics (CFD) and machine learning approaches, already applied in marine hydrodynamics, may be extended to external gear pumps for predicting flow efficiency and resistance. Together, these avenues position additive manufacturing not only as a prototyping tool but also as a pathway toward advanced, AI-integrated, polymer-based gear systems.

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Figures

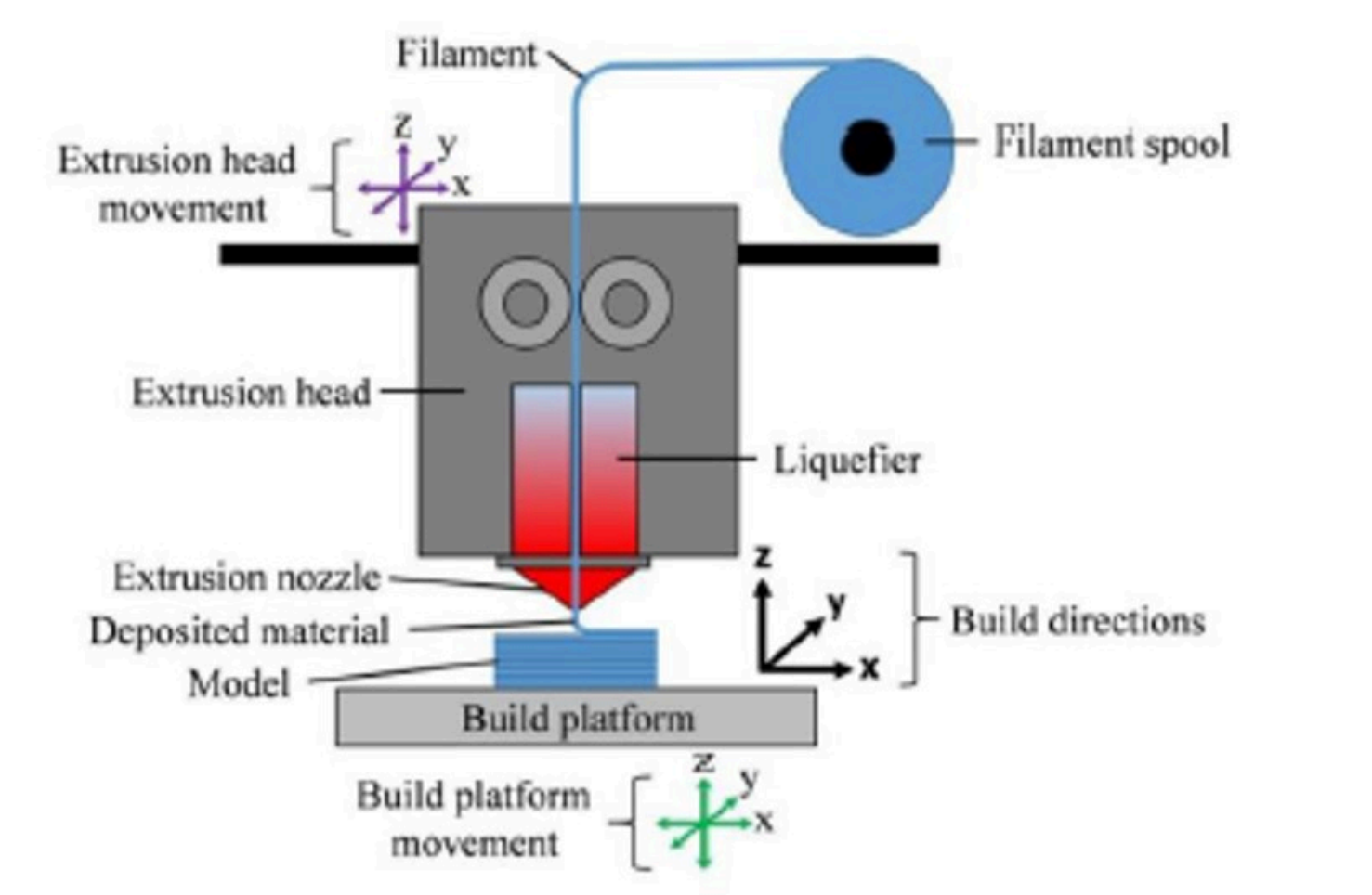


Figure 1

Material Extrusion based AM process

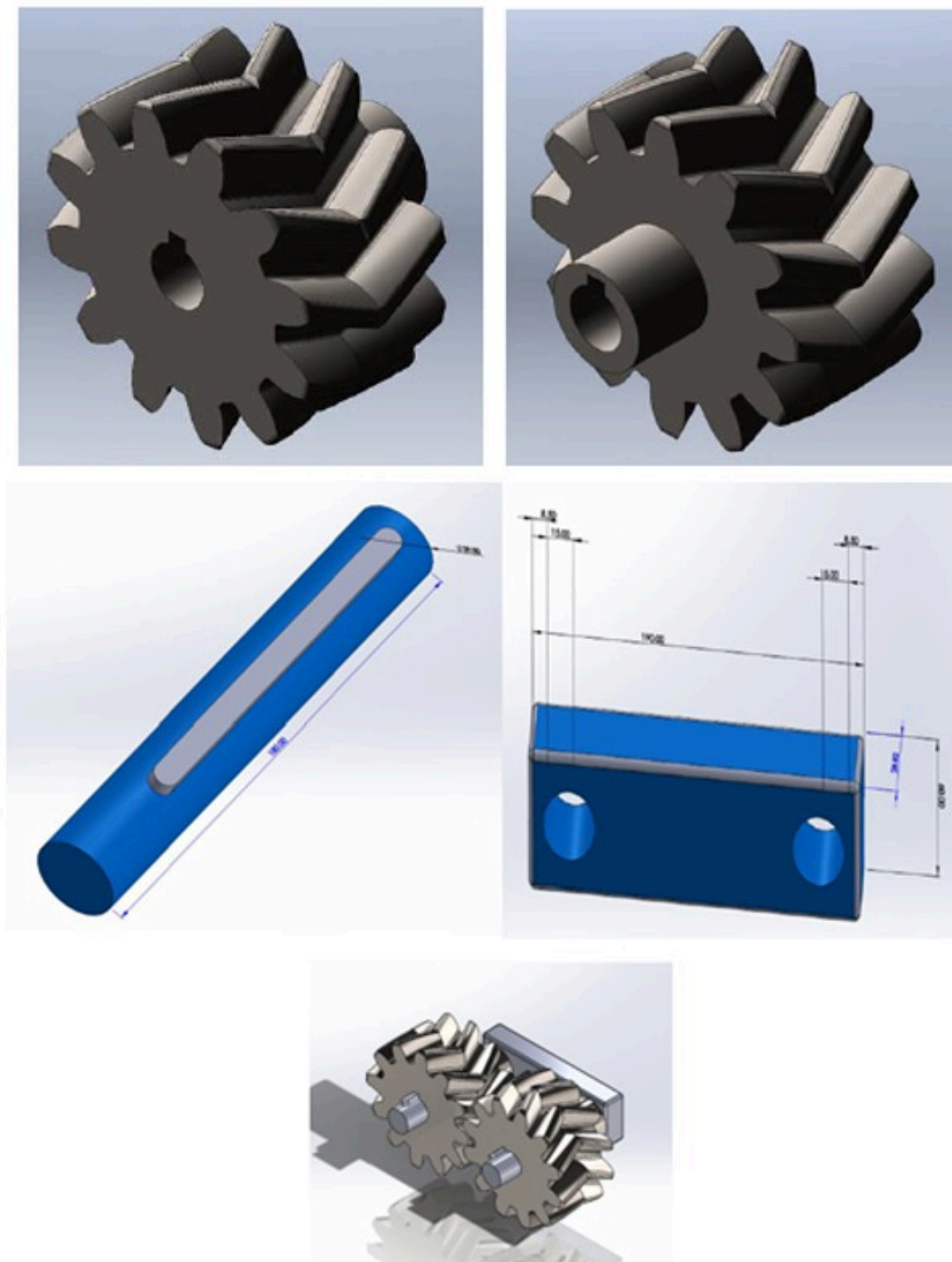


Figure 2

CAD model of left-helix direction gear (top-left), right-helix direction gear (top-right), shaft (middle-left), bracket (middle-right), and assembly (bottom)

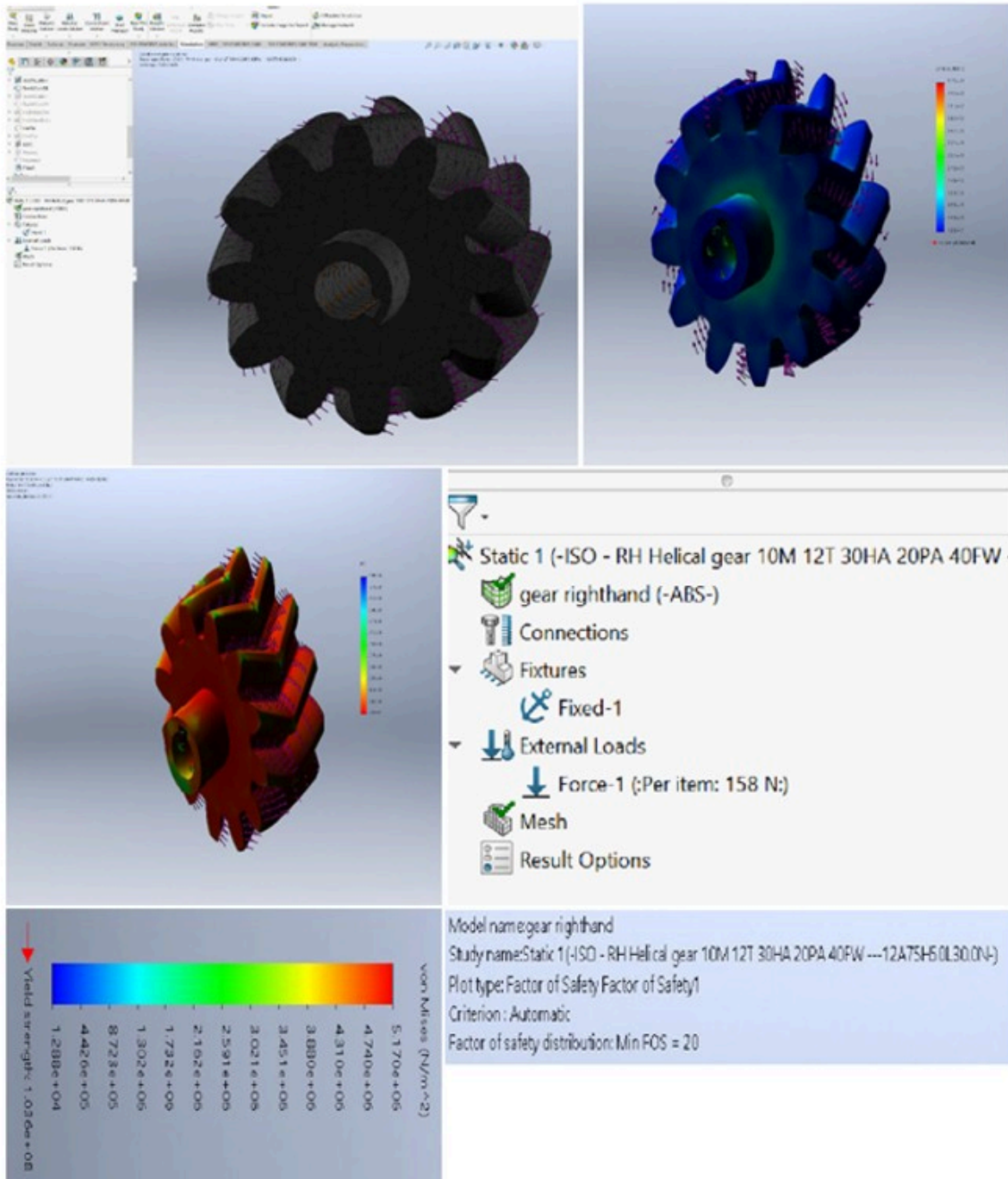


Figure 3

Loading and meshing (top-left), Von Misses stress after simulation (top-right), factor of safety after simulation (mid-left), zoomed loading and material conditions (mid-right), zoomed Von Misses stress vs yield strength (bottom -left), zoomed factor of safety (bottom-right)

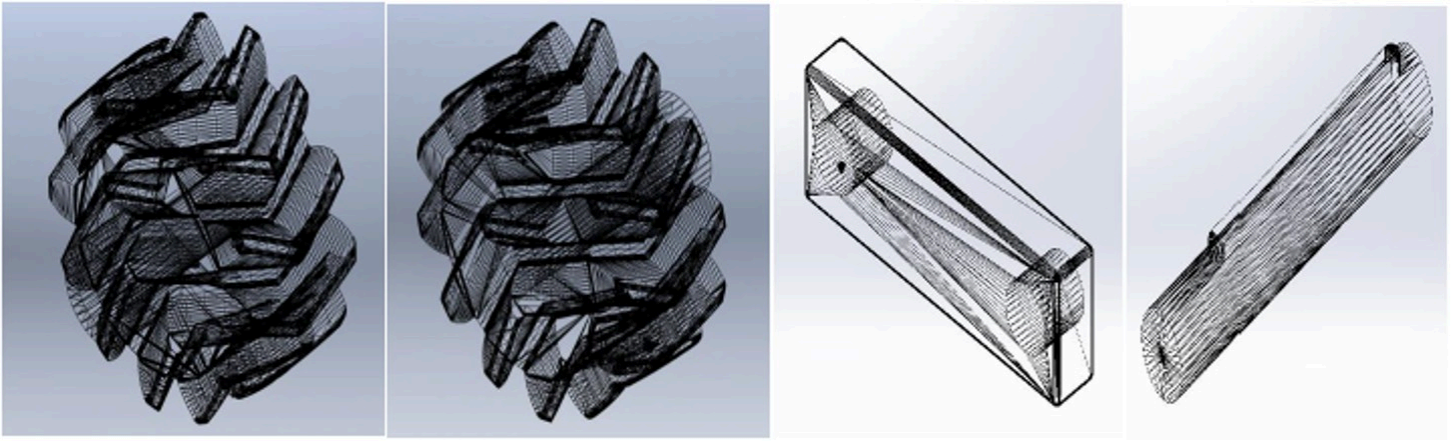


Figure 4

STL Mesh of right-helix direction gear (left), left-helix direction gear (mid-left), bracket (mid-right) and shaft (right)

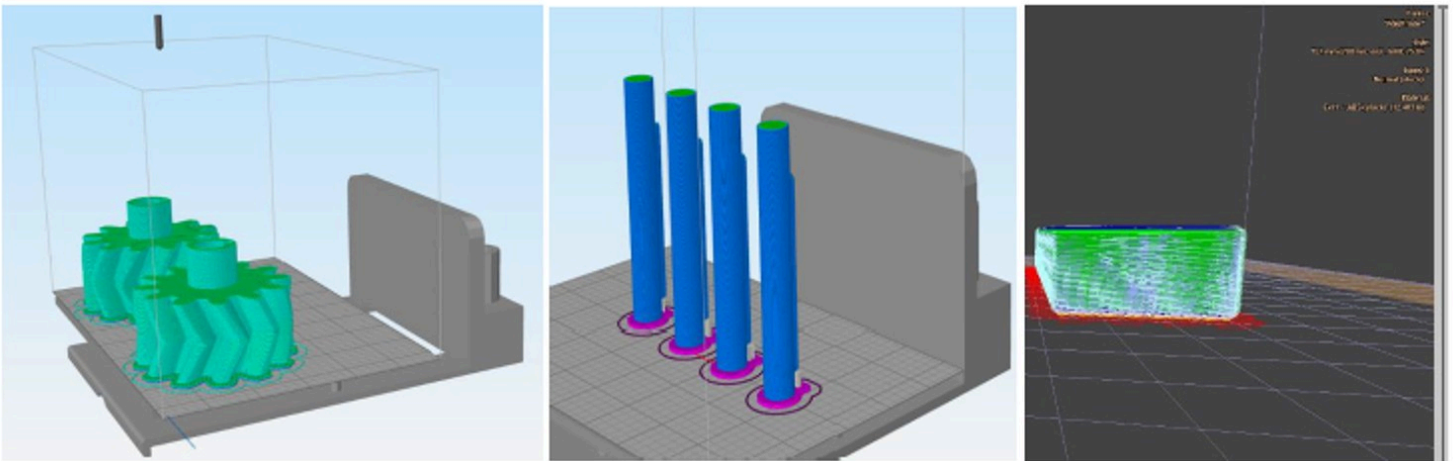


Figure 5

STL file in Simplify3D of gears (left), shaft (middle), and bracket (right)

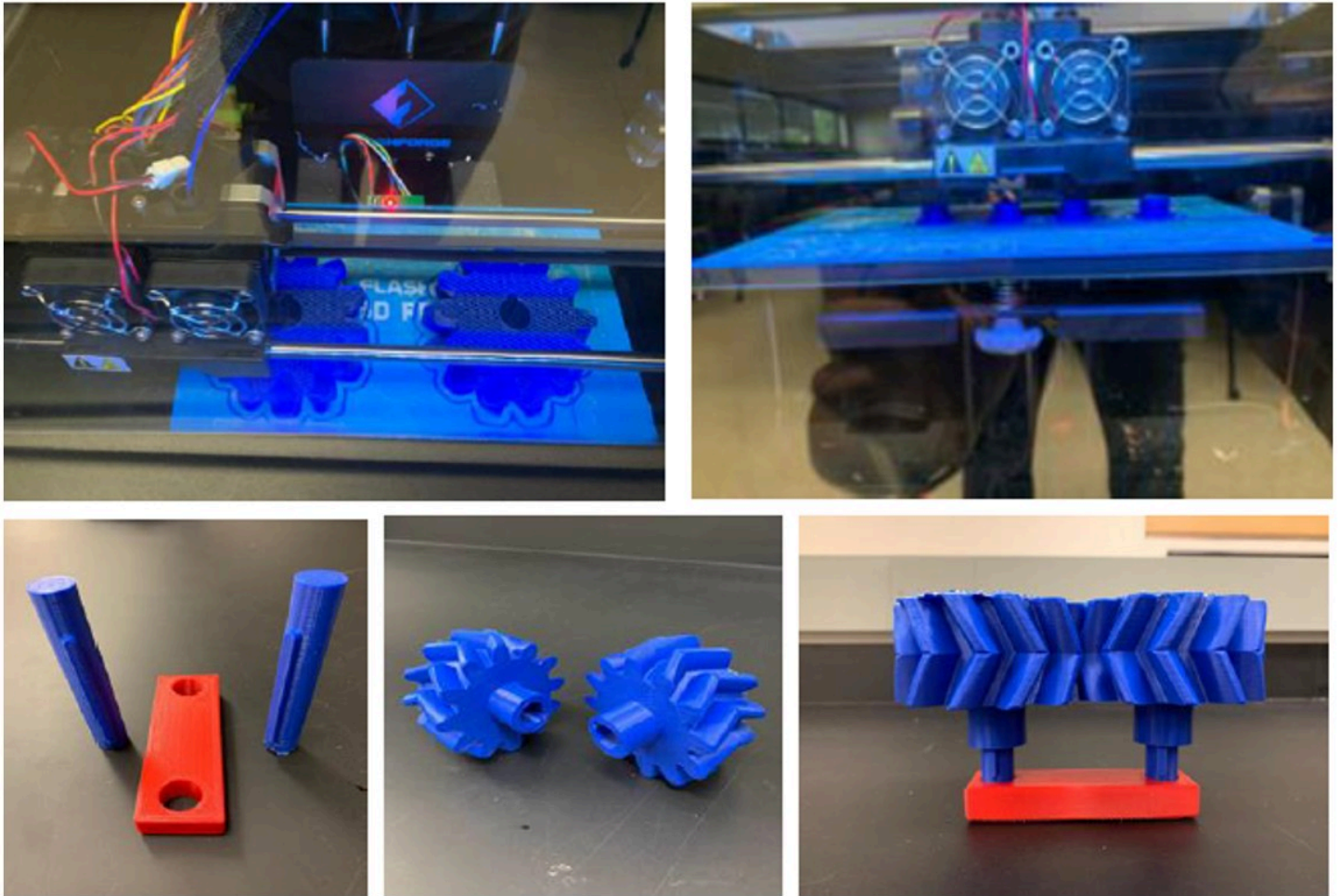


Figure 6

During printing of gears (top-left), during printing of shafts (top-right), printed shafts and bracket (bottom-left), printed gears (bottom-middle), and printed functional assembly (bottom-right)