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Planetary Gearbox Design and Development using Additive Manufacturing

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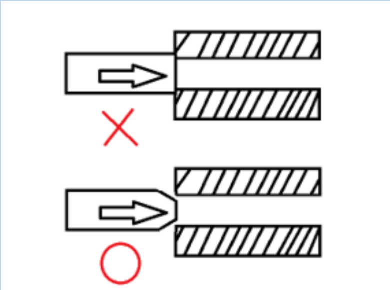
Abstract: Modern manufacturing technology is dominated by additive manufacturing due to its simplicity, precision, time and material savings, and flexibility in design. The purpose of this study is to propose and print a 3D model of planetary gear trains since these gear trains are more efficient than conventional gear trains and have many advantages. A planet gear trains must have collinear input and output axes in order to achieve compact space requirements. Using even spacing between the planets in a gear train allows both static and dynamic forces to be balanced. It is also possible for multiple planets to produce high torques. Finally, it is capable of providing a wide range of speeds. The printed model performed exceptionally well when it came to performance, and it can be used for both educational and industrial purposes, exhibiting the ability to withstand a high level of stress. The current paper demonstrated the process of 3D printing and the challenges involved in printing planetary gear trains, as well as possible solutions to these challenges. Finally, tolerances were reported as 0.5 mm on the final CAD model, and 0.15 mm on the last updated results.



Keywords: Additive Manufacturing; Assembly; 3D printing; Planetary gearbox system

Introduction

Additive manufacturing (AM) or rapid manufacturing (RM) is widely used in many aspects of life. The technology is also known as layered manufacturing, rapid prototyping, and 3D printing. In this operation, physical products are produced directly from 3D computer data by layer-dominated manufacturing processes. Steel bridges, the artificial heart pumps, jewelry collections, shoes, hydrogen fueled rocket engines (PGA), and other mechanical parts like a door bracket for the Airbus A350-1000 are all manufactured using digital fabrication techniques. In addition, printed firearms are being used by the military. 3D printing applications emerged following the fabrication of the first 3D printer in 1980 and the registration of the first patent in 1989. [(1-7)]

In today's world, 3D printers can print complex geometries using a variety of materials, such as alloys and metals, polymers and composites, ceramics, concrete, thermoplastics, and so on.[8] 3D printing is a type of additive manufacturing that involves building up models and products layer by layer. [(9)] Subtractive manufacturing (SM) is another type of manufacturing. In this technology, the required model is subtracted from a large printed model. As a result of its simplicity, precision, time-saving, and material-saving characteristics, versatility in design, and low cost, additive manufacturing is in high demand. [(10,11)] As an example, the artificial heart pumps and artificial jaws can be substituted for very costly products with cheaper and more effective alternatives. [(12)] Despite this, these products do not constitute prototyping. In other words, they are actual replacements for the originals. 3D printing can be classified into seven types according to their applications. Refer to ASTM Standard F2792 and for more information. 3D printing methods include fused deposition modeling (FDM), powder bed fusion, inkjet printing and contour crafting (CC), stereolithography (SLA), direct energy deposition (DED), and laminated object manufacturing (LOM). [(13,14)]

As part of the 3D printing process, the design of a 3D model of the product is the first step. In order to process the model for rapid manufacturing, a 3D model is exported to the pre-processing software of the machine. [(15)] Initially, pre-processing involves an automated process that divides the complex 3D model into a stack of 2D disks. From this stack, an accurate representation of the 3D model can resemble. A higher layer count means a closer approximation of the 3D geometry. Depending on the type of RM process, the second process step for each disk involves lines or dots that describe the disk accurately. In this case, a rapid manufacturing machine can be programmed with the desired location of the lines or dots (per layer). Figure 1 depicts a 3D model of a cone (top left), the cone divided into layers (top right), the cone approximated by stacking 2D geometry layers (bottom left), and the approximated layer by a series of lines (bottom right).

Rapid manufacturing machines are essentially very simple machines. An example of RM is FDM, which involves the feeding of plastic wire through an extrusion head. This results in a continuous line of molten plastic. When plastic is deposited, the

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extrusion head moves from location A to location B while the machine is extruding. By repeating this process many times, a layer will be created. By moving the thickness of one layer in the z-direction, it is able to create the second layer. According to the example above, each layer is smaller than its parent layer. The printing process will be different when trying to print more complex shapes. When printing an overhanging geometry, it cannot be suspended in mid-air. Supports should be provided by some materials, not included in the final product. Support materials are used to support overhanging features on FDM machines. As shown in Figure 2, this material can be broken away from the product or dissolved in water. It is possible that the intended second product layer will not be fully supported by the product material in its underlying layer (up). In this case, the lower layer will utilize both product and support materials (red; down). It is then implemented to print using melt extrusion. There are, however, different cooling rates (shrinkage) at different points of the cooling process. In this case, there is the possibility of deformation or even bending due to the fact that the print segments are taken. Even though polylactic acid (PLA) shrinks less than acrylonitrile butadiene styrene (ABS), both have the same strain issue that might ruin printing works in the worst-case scenario. The materials used for FDM can be ABS filaments, iron filaments (iron powders mixed with PLA), conductive filaments (conductive carbon mixed with PLA), and metal powders for selective laser melting (SLM). A major factor in resisting high stresses and vibrations is the material used for printing. By selecting the right printing material, such issues can be easily resolved.

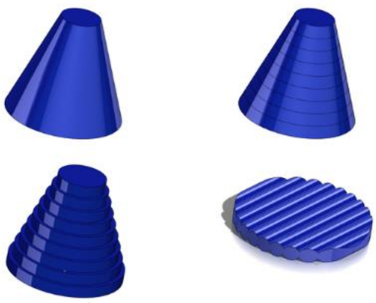


Figure (1): A 3D model for a cone

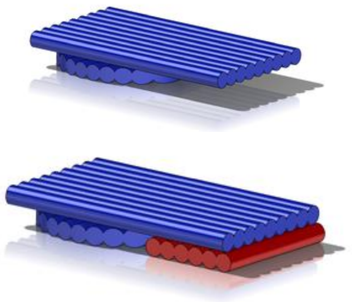


Figure (2): Model supporting material

The planetary gearbox has been chosen for this study since it is used in a wide variety of mobile mechanical systems such as cars, planes, and boats where power and torque must be transmitted. Additionally, these trains have many advantages over ordinary gear trains. When the input and output axes are collinear, the planetary gear train model would have a compact footprint. It should be also noted that when multiple planets are evenly spaced about the gear train's central axis, static and dynamic forces are balanced. Moreover, using multiple planets can increase torque capacity. Finally, it provides a wide range of speed ratios.

Although these trains are of great importance, they are also subject to a number of challenges, including vibration, frequency diagnosis, their motion, and so forth. [16-19] The result is that geometrical real-time tests are difficult and cost a considerable amount of money. [20,21] Yet, it would be possible to fabricate planetary gear trains in 3D for testing at a low cost. The present research aims to design and print planetary gear trains for educational and industrial use. [22]

Section 2 describes the design progress of the planetary gearbox system. Results and discussion are presented in section 3 while conclusions are presented in section 4.

DESIGN (FIXER)

Planetary Gearbox System

Gears have six nouns that describe the gear parts: (1) module, (2) base circle, (3) pitch circle, (4) addendum circle, and dedendum circle, (5) clearance, and (6) planetary gear train.

1) Module (M): It represents the shape of the gear body in the metric system. Basically, it is the ratio of the diameter of the pitch circle (d) to the number of gear teeth (N). An example of a module part with 8 teeth and a diameter for a gear is shown in Figure 3.

$$M = \frac{d}{N} \tag{1}$$

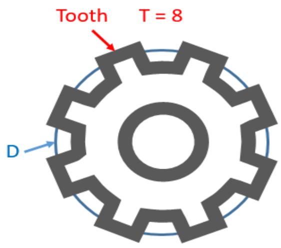


Figure (3): Gear diameter and teeth

2) Base circle: A gear's base circle is the circle tangled to the force line when it matches up with another gear. In meshing, the force is the line contact along the contact point.
3) Pitch circle: Two gears in mesh have a point that is crossed by the force line, and that point is called the pitch point. The radius of the pitch circle is the distance from the pitch point to the gear's center.
4) Addendum circle and the dedendum circle: Addendum circles represent the radial distance between the tops of gear teeth to the center, while dedendum circles represent the radial distance between the bottom lands between teeth to the center.
5) Clearance: The distance between the addendum circles of one circle and the dedendum circles of the other circle.
6) Planetary gear train: Planetary gear trains have at least one gear whose axis moves on a circular path in relation to its base link

Figure 4 illustrates the gear used in the current research. Pitch circle diameters have the following geometrical relationship as shown in equation (2) where the number (1, 2, 3) are taken from Figure 4 as described below.

$$d_1 + 2d_2 = d_3 \tag{2}$$

For all gears to mesh, they must have the same module. Therefore, all meshing gears must have the same pitch in this instance. Thus:

$$N_1 + 2N_2 = N_3 \quad (3)$$

Then,

$$N_2 = \frac{N_3 - N_1}{2} \quad (4)$$

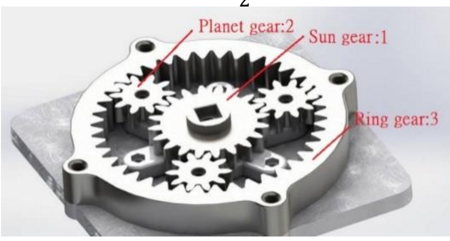


Figure (4): Planetary gear train

To determine the reduction rate of the planetary gear train, it is important to know the relationship between the speed of the gears, see Figure 4. Table 1 describes the current design parameters. Equation 5 show the gear ratio (i) for the current planetary gear system:

$$i = \frac{\omega_1}{\omega_2} = \frac{O_2P}{O_1P} \quad (5)$$

where ω is the angular velocity. And,

$$\frac{\omega_1}{\omega_2} = \frac{R_2}{R_1} = \frac{d_2}{d_1} = \frac{N_2}{N_1} \quad (6)$$

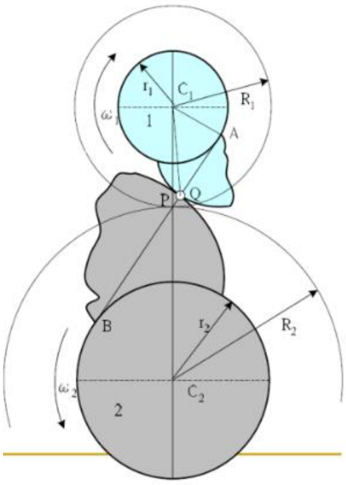


Figure (5): Speed relationship of gears [23]

Table (1): Design Parameters

	Teeth number, N	Diameter, d (cm)
Sun gear: 1	20	5.0
Planet gear: 2	10	2.5
Ring gear: 3	40	10.0

For the module of 2.5 mm, the diameter from the formula:

$$d = N \times M \quad (7)$$

Assuming the planet gear is fixed, and letting the sum gear be the input, the following speed relationship based on the speed formula can be formulated:

$$\frac{\omega_2}{\omega_1} = -\frac{R1}{R2} = -\frac{d1}{d2} = -\frac{5}{2.5} = -2$$

$$\frac{\omega_3}{\omega_1} = -\frac{R1}{R3} = -\frac{d1}{d3} = -\frac{5}{10} = -0.5$$

If the planet carrier rotates, the speed of the planet carrier should be considered and the following formula should be used (see Figure 6):

$$\begin{aligned} \omega_1 &= x + y \\ \omega_2 &= x \\ \omega_3 &= x - \frac{N_1}{N_3}y \\ \omega_4 &= x - \frac{N_1}{N_4}y \end{aligned} \quad (8)$$

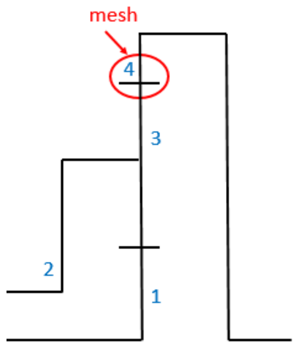


Figure (6): The speed of the planet carrier.

There are a few types of planetary gear trains, but the basic one is used. This device is primarily used for providing a wide range of speed ratios. High torque capacity can be achieved by using multiple planets. There are many applications for planetary gear sets, such as automatic transmissions. In this mechanism, there are many gears, including sun gear, ring gear, planetary, and carrier in a variety of combinations. As an example, consider a hypothesis in which the sun gear has 30 teeth and the ring gear has 100 teeth. Having 130 teeth (100+30), the planetary has 130 teeth. Detailed information about planetary gear trains can be found in Table 2 below.

Table (2). The main conditions for the planetary gear train.

	Condition	Transmission ratio	Results (speed, torque)
1	Planetary fixing, power from sun gear to ring gear (counter-clockwise). It is usually used in reverse	100/30=3.33 (>1)	speed reduces, torque increases
2	Planetary fixing, power from ring gear to sun gear (counter-clockwise)	30/100=0.33 (<1)	speed increases, torque reduces
3	Ring gear fixing, power from sun gear to carrier	130/30=4.33 (<1)	speed reduces, torque increases
4	Ring gear fixing, power from planetary to the sun gear	30/130=0.23 (<1)	speed increases, torque reduces
5	Sun gear fixing, power from ring gear to carrier	130/30=4.33 (>1)	speed reduces, torque increases
6	Sun gear fixing, power from carrier to the ring gear	30/130=0.23 (<1)	speed increases, torque reduces
7	Any two parts are fixed in planetary gear	1	no change

Designing Procedure

Designing consists of three main steps, namely ideas collection, final design drafting, and computer-aided design (CAD) model completion based on the final draft. Assembling different types of one-stage planetary gearbox systems is the basic idea. Discussions focus on orientation, housing, jointing the components, and mechanisms of reduction rate adaptation. This means that the input and output roles are changed using a reduction system with necessary components mounted on a plate.

Several ideas are adopted. First, fixing the components to the plate with a pin or bolt serves as a constraint for each arrangement of different reduction rates. Secondly, there is an extra reinforcement fillet around the horizontal bar on the T-shaped handler. This mechanism locates around the tip of the component and functions as a guide during assembly if there are any unexpected deformations or irregular surfaces near the contact point. Other components' designs could be adapted in this way, see Figure 7.

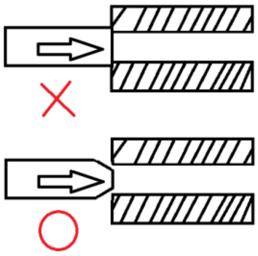


Figure (7): Axial constraint fitting issue and how to fix it.

In addition to the axial constraint of the rotational parts, it is important to emphasize the rotational parts' axial movement. If this constraint were not present, there would be vibrations in each component, causing a collision to damage the components near the contact region.

A creative alternative to fixing planet gears to the frame would be to use bolts and nuts. In order to avoid machining issues, larger teeth are used instead of a printed component with an orientation that might cause weakness in the design. Therefore, the bolts and nuts are in the frame.

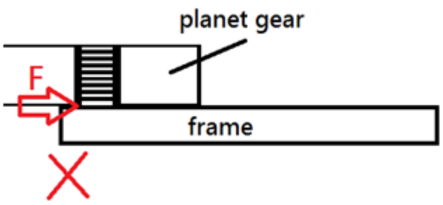


Figure (8): Vibration's constraint fitting issue.

The final CAD model is then generated with a tolerance of 0.5 mm factored on all dimensions, as shown in Figure 9. Figure 10 shows each component with its proper fillets.

Figure (9): CAD model design.

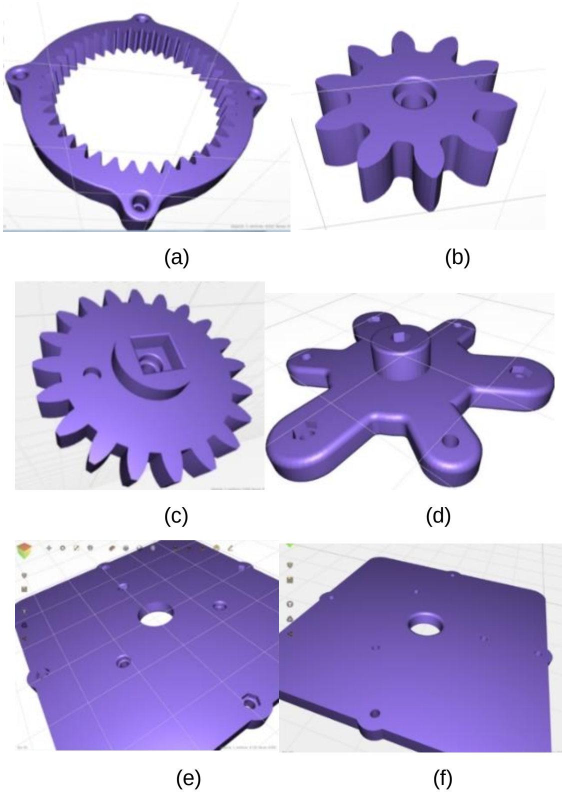


Figure (10): CAD model components: (a) Ring gear, (b) Planet gear, (c) Sun gear, (d) Carrier, (e) Bottom of the plate, and (f) Top of the plate.

3D Printing (Design Preparation and Slicing)

The 3D printer used in this work is an AURORA 3D printer F1 as shown in Fig. 11. This printer can produce sharp details with high accuracy. The printer has an overall dimension of 450×420×460 mm^3, a body net weight of 19 kg, a building envelope range of 168×168×168 mm^3, a minimum printing layer thickness of 0.1 mm, a nozzle diameter of 0.4 mm (±0.05mm), and PLA as a print material has been unutilized with a diameter of 1.75mm (±0.1mm). The lower melting point of PLA makes it a suitable material for use. In addition, PLA can be successfully printed without the need to heat the printing bed. As PLA becomes hotter, it becomes more liquid, resulting in giving sharper details during printing.

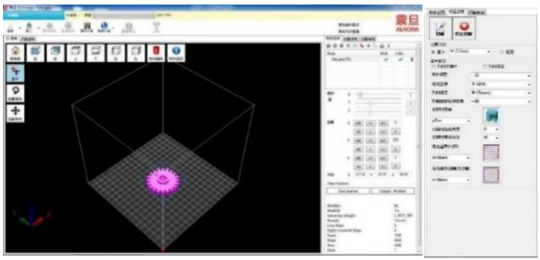
Figure (11): Vibration's constraint fitting issue.

For the printing process to be completed, some steps must be followed after the draft and CAD drawing have been made:

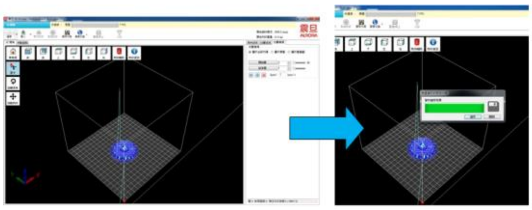
- Save the CAD file as an STL file within 15×15×15 cm^3 limited 3D of the assembly model, Figure 12(a).
- Use Netfabb Professional 5.2 software to check if the STL files have errors or not in order to repair them, Figure 12(b).
- Start slicing via the slicing software, Figure 12(c).
- Save the G-code and save it on the SD card, Figure 12(d).
- Insert the SD card in the 3D printer port for printing.

(a)

(b)



(c)

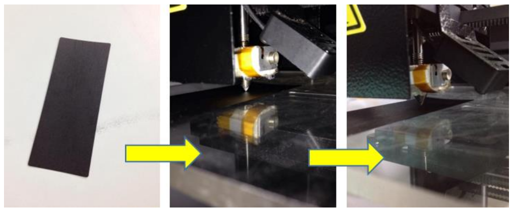


(d)

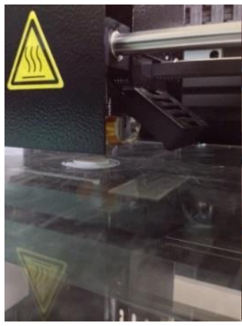
Figure (12): Printing procedure: (a) save the CAD file as an STL file, (b) check the STL file, (c) slice, and (d) save the sliced file on an SD card.

Results and Discussion

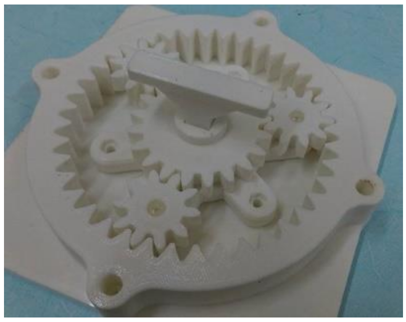
Upon printing and putting the design to practical testing, the results will be shown. A side-by-side comparison of the printing process and the final design can be seen in Figure 13. Calibration via the scale ensures that the working plane is horizontal and the nozzle head is vertical with the plane, allowing the printing process to continue. After that, the nozzle head should be positioned at its original position. Generally, it is done to determine the orientation of the parts, the design of the raft and support, and the parameters of the processing. Nevertheless, the material should be heated after the printer is turned on. Temperatures range from room temperature to 200 °C. A temperature range of 200 °C to 220 °C is required for printing. Lastly, all the parts are printed and the planetary gearbox system is assembled as shown in Figure 13(d).



(a)



(b) (c)



(d)

Figure (13): Printing procedure: (a) Calibration level, (b) Setting the nozzle head and start printing, (c) Printed parts, and (d) Final model assembly.

In the final CAD model, the printed parts were so precise with a tolerance of 0.5mm on the final CAD model, and 0.15mm on the latest updated results, giving a very high level of accuracy. It means that even small details can be printed effectively because of this technology. In the current case, gearbox systems are being manufactured with the help of 3D printers. Besides the educational or industrial purposes for which the produced parts can be used, the process of 3D printing can also be demonstrated in detail in the educational or industrial settings. It is also noteworthy that this study has shown some of the challenges that 3D printing faces as well as some of the solutions that have been proposed to solve them.

According to the results of this study, 3D printing has a number of benefits for planetary gearbox systems, including improved accuracy, reduced material waste, and cost savings. The use of 3D printing eliminates the need to fabricate complex parts, thus saving time and reducing the costs associated with CNC machining. Furthermore, 3D printing produces less waste than traditional manufacturing methods. Finally, 3D printing reduces manufacturing costs in comparison with traditional methods, resulting in overall cost savings.

Conclusion

The present paper presents a 3D model of planetary gear trains and demonstrates how additive manufacturing can be used to generate it using additive manufacturing, a technology that is gaining popularity due to its simplicity, precision, cost-savings, and design flexibility. Planetary gearboxes printed by 3D printing can be used in both education and industry. This research examined the printing procedure in detail along with the challenges associated with it. Furthermore, potential solutions to those challenges have been presented. As a result, this type of printed model performed exceptionally well. Lastly, tolerances of 0.5mm are applied to the final CAD model, and the latest update indicates a tolerance of 0.15mm.

The printed parts will be tested in a real industrial system in the upcoming study. Additionally, AD will be evaluated for its suitability to print multi-material as well as printed circuit boards (PCB). The next study will consider using two or more different materials, one of which is conductive. Finally, artificial intelligence (AI) such as internet of things (IoT) paradigm with ensemble machine learning (ML) will be added for to detect any unexpected faults and energy saving.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.

Author's contribution

The authors contributed equally to this work. All authors reviewed the results and approved the final version of the manuscript.

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Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this article

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Nomenclature

AI Artificial Intelligence

AM Additive Manufacturing

CAD Computer-Aided Design

CC Contour Crafting

d Pitch Circle Diameter, cm

DED Direct Energy Deposition

FDM Fused Deposition Modeling

i Gear Ration

IoT Internet of Things

LOM Laminated Object Manufacturing

M Module

ML Machine Learning

N Number of Gear Teeth

PCB Printed Circuit Boards

PGA Hydrogen Fueled Rocket Engine

R Radius, cm

RM Rapid Manufacturing

SLA Stereolithography

SM Subtractive Manufacturing

<u>Subscripts:</u>

1 Sun Gear

2 Planet Gear

3 Ring Gear

References

1) Rasiya G, Shukla A, Saran K. Additive Manufacturing-A Review. Materials Today: Proceedings; 2021; 47(19):6896-6901.
2) Srivastava M, et al. A review of various materials for additive manufacturing: Recent trends and processing issues. Journal of Materials Research and Technology; 2022; 21:2612-2641.
3) Mhetre GN, et al. A Review on Additive Manufacturing Technology. ECS Transactions; 2022; 107:15355.
4) Birtchnell T, Urry J. 3D, SF and the Future. Futures; 2013; 50:25-34.
5) Hull C. Apparatus for production of three-dimensional objects by stereolithography. US Patent 4,575,330; 1986.
6) Holzmann P, et al. User entrepreneur business models in 3D printing. Journal of Manufacturing Technology Management; 2017; 28(1):75-94.
7) Li DF, Chen JM, Yuan YP, Huang K, Fang HB. Development and application of stereo lithography apparatus. Journal Beijing Univ Technol; 2015; 41:1769-74.
8) Ze-Xian L, et al. Perspective on 3D printing of separation membranes and comparison to related unconventional fabrication techniques. Journal of Membrane Science; 2016; 523(1):596-613.
9) Campbell T, et al. Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing. Atlantic Council; 2011.
10) Ian G, DWR BS. Additive manufacturing technologies. Rapid prototyping to direct digital manufacturing. US: Springer US; 2010; 1-459.
11) Ferreira I, et al. State-of-the-Art review and roadmap. In: Torres Marques A, et al., editors. Additive manufacturing hybrid processes for composites systems. Springer International Publishing: Cham; 2020; Vol. 1-56.
12) Masood SH. Advances in Rapid Manufacturing and Tooling. Comprehensive Materials Processing, Elsevier Science Direct, Glasgow; 2005; 69-91.
13) ASTM F2792-12a. Standard terminology for additive manufacturing technologies. ASTM International. West Conshohocken, PA; 2012.
14) Shahrubudin N, et al. An Overview on 3D Printing Technology: Technological, Materials, and Applications. 2nd International Conference on Sustainable Materials Processing and Manufacturing (SMPM 2019), Procedia Manufacturing; 2019; 35:1286-1296.
15) Jandyal A, et al. 3D printing – A review of processes, materials and applications in industry 4.0. Sustainable Operations and Computers; 2022; 3:33-42.
16) Olegovna Gorshkova O, Ivanovich Nekrasov V. Planetary gearbox 5R2. International Journal of Mechanical Engineering and Technology; 2018; 9(11):1984-1991.
17) Figlus T, et al. The Effect of Selected Operational Factors on the Vibroactivity of Upper Gearbox Housings Made of Composite Materials. Sensors; 2019; 19:4240.
18) Figlus T, et al. Impact of Application of Selected Composite Materials on the Weight and Vibroactivity of the Upper Gearbox Housing. Materials; 2019; 12:2517.
19) Wojnar G, et al. Multidimensional Data Interpretation of Vibration Signals Registered in Different Locations for System Condition Monitoring of a Three-Stage Gear Transmission Operating under Difficult Conditions. Sensors; 2021; 21:7808.
20) Brumercik F, et al. Comparison of Selected Parameters of a Planetary Gearbox with Involute and Convex–Concave Teeth Flank Profiles. Applied Sciences; 2020; 10:1417.
21) Zou H, et al. Improved algorithm of tooth surface topological modification and nonlinear dynamic analysis of herringbone gears. Mechanism and Machine Theory; 2023; 180:105151.
22) Smajic J, et al. Planetary Gearbox Prototype Development and Manufacturing. Tehnički glasnik; 2021; 15(4):534-540.
23) NTPC Education. [Internet] 2023 [cited 2023 August 30]; Available from: https://www.scvs.ntpc.edu.tw/p/412-1000-235.php.