



TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering  
Vol. 69, Issue Special I, February, 2026

## A STUDY ON ADDITIVE MANUFACTURING AS AN ENVIRONMENTALLY SUSTAINABLE METHOD FOR PRODUCTION OF TOOTHED GEARS

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**Abstract:** Additive manufacturing, or 3D printing, is used globally with big leaps being taken in various important fields, for example in mechanical and mechatronics engineering areas. The purpose of the article consists in the analysis of additive manufacturing methods of gears, as well as their application for obtaining gear samples, which will be analysed both dimensionally and visually. Different additive technologies were compared with the aim of choosing the optimal one so that during manufacturing the environment is not polluted, the 3D printer does not have any loss of toxic material (which is recyclable), but at the same time we want to obtain a transmission that is durable over time and allows for fast manufacturing process with relatively low costs.

**Key words:** Additive manufacturing, Gear manufacturing, Environmentally sustainable manufacturing, Low-waste technology, Rapid Prototyping, 3D printing.

### 1. INTRODUCTION

Additive manufacturing (AM) or 3D printing (3DP) are among the latest manufacturing processes used for creating objects based on 3D models generated from various design software. This innovative method allows for the fabrication of parts by combining a range of materials including plastic, metal, ceramic, or composite materials. Unlike traditional manufacturing technologies such as cutting or casting, which require extensive processing, additive manufacturing builds objects layer by layer, offering the capability to produce parts of varying complexity without the need for additional finishing processes.

There are seven main categories of additive manufacturing technologies, as identified by researchers including: powder bed fusion, material jetting, thermal extrusion, vat photopolymerization, and binder jetting, according to the standard terminology for additive manufacturing-general principles-terminology that are well established and

referenced in the ISO/ASTM 52900-15 document [1]. These technologies are continuously evolving, with a particular focus on applications in mechanical and mechatronic engineering fields.

The widespread adoption of additive manufacturing is driven by its numerous advantages, including the ability to produce durable and resilient parts at a relatively low manufacturing cost. Among these advantages, it can be mentioned the possibility of creation of parts with complex geometries from different plastic, metal, ceramic, or composite materials, obtaining fine details and complex parts, such as gears with unconventional profiles and geometrical parameters, that is very difficult or even impossible to obtain through traditional methods, which involve high costs and energy consumption, use of undesired substances for equipment maintenance, and materials that are not friendly to nature. That is why the manufacturing of gears through additive technologies is much more advantageous in terms of low costs and energy consumption, use

of eco-friendly materials and not least, the more sustainable approaching of using raw materials which lead to the lower waste. However, alongside its benefits, it is crucial to consider the environmental impact of AM processes. Various analyses have been conducted to assess factors such as electricity and material consumption, as well as strategies for recycling unused or excess material, all aimed at promoting the sustainability of additive manufacturing. The concept of the circular economy also plays a significant role in minimizing waste and maximizing resource efficiency within the AM process [2,3].

The biggest impact on the environment is the manufacturing of different gears, because they are the main mechanical components that have the role of transmitting the movement and/or power of machines, tools, equipment, or robots. According to the studies [4], the gears are manufactured on a large scale globally, which means that once there are made by conventional methods, the need for the finishing process appears, in which the energy consumption is very high and different tools are used that require lubrication using oils and undesired substances, which can affect human health and the environment. However, the finishing process is still necessary to improve the quality of the surfaces that have undergone the machining process. All this affects sustainability, so, it is very important to manufacture gears and gear transmissions using modern methods, such as additive manufacturing technologies [5,6,7,8].

## **2. ADDITIVE TECHNOLOGIES OVERVIEW**

According to research [9,10] the principle additive technologies depend on the type of base used and the type of material processing. It is more environmentally safe to use these additive technologies, unlike the usual ones that use processing by casting or cutting different metal materials, as specified in Section 1. These additive technologies are presented in the diagram below (Fig. 1).

The following lines will specify some particularities for the main additive technologies. The additive manufacturing

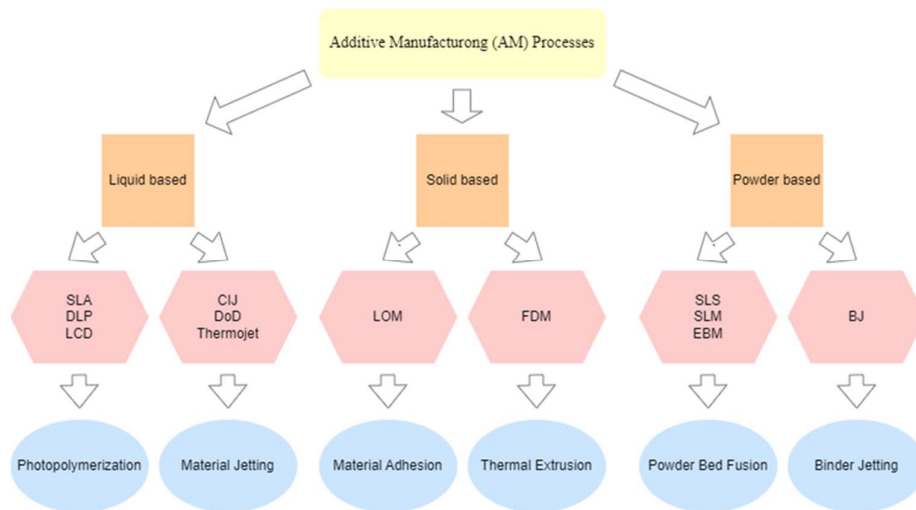
technologies of Stereolithography (SLA), Digital Light Processing (DLP), and Liquid Crystal Display (LCD) are based on photopolymerization, whereas Continuous Inkjet (CIJ), Drop-on-Demand (DoD), and Thermojet technologies employ material jetting for part fabrication.

Stereolithography (SLA) is an additive manufacturing technique that utilizes a laser source positioned above the build platform to selectively cure a liquid polymer resin. The laser beam traverses the liquid reservoir, inducing localized polymerization along its path. A key advantage of SLA technology is its capacity to produce high-resolution, solid three-dimensional structures through the successive layering of liquid material [11,12]. This process yields rigid, highly detailed prototypes with a substantial degree of material density. While various commercial laser-based lithographic techniques exist, SLA is regarded as the foundation of 3D printing technology and continues to be among the most widely employed additive manufacturing methods. Its primary benefits include a well-balanced combination of speed, resolution, and build volume. Additionally, SLA-printed components exhibit high durability and excellent moisture resistance, making them particularly suitable for underwater applications [9,13].

Additive vat-polymerization technologies, such as Digital Light Processing (DLP), employ a micro-mirror device to facilitate localized polymerization of the resin from which objects are fabricated [14]. Unlike SLA, DLP technology enables uniform curing of entire layers simultaneously, eliminating the need for post-solidification processing [15].

From a sustainability perspective, the mechanical and thermal properties of the resins used in DLP printing are critical, as enhanced material resilience can extend the functional lifespan of printed components [16,17].

Liquid Crystal Display (LCD) 3D printing leverages LCD screens to direct light onto the resin, ensuring precise polymerization. A fundamental advantage of LCD technology is the absence of light expansion, which mitigates pixel distortion—an issue commonly observed in DLP printing.



**Fig. 1.** Classification of additive manufacturing processes

Furthermore, LCD printing does not require detailed scanning of the photopolymer, as is necessary in SLA, thereby increasing printing efficiency. Most LCD printers utilize UV or LED lamps to illuminate the resin. Another key aspect of LCD printing is the incorporation of oxygen permeation to inhibit radical polymerization, which facilitates rapid and continuous printing [18,19].

Material jetting technologies in 3D printing primarily include Ceramic Ink Jet (CIJ) and Drop-on-Demand (DoD) methods. In CIJ additive manufacturing, a continuous flow of liquid material is deposited layer by layer through a pressurized nozzle system. CIJ printers may incorporate multiple nozzles, and the material jet is fragmented into droplets, which attain a size approximately twice the diameter of the nozzle opening [20,21].

Drop-on-Demand (DoD) additive technology functions by depositing material in discrete volumes, like conventional polymer inkjet printing. A major advantage of DoD technology, particularly in liquid metal 3D printing, is its streamlined workflow. Unlike conventional metal additive manufacturing (AM) processes, which often require intricate handling of metal powders, DoD technology enables direct digital deposition of metal. Additionally, this technology facilitates multi-material printing, in contrast to traditional metal AM systems that are typically limited to a single material type [22].

Laminated Object Manufacturing (LOM) is an additive process that involves the lamination of foils or paper to construct a part. This technology was initially developed to assess material resistance and behaviour under elevated temperatures. Moreover, LOM enables the evaluation of various process parameters, such as printing speed, laser cutting duration, and ambient temperature effects on manufacturing quality. The primary advantages of LOM technology include its low cost, rapid processing speed, and material versatility, as it supports a wide range of substrates [17,23,24].

Fused Deposition Modelling (FDM) is the best-known and most-used additive technology globally. This additive technology is based on thermoplastic extrusion [25].

The manufacture of parts using FDM technology implies, like the other additive technologies, low costs; different materials can be used with good thermal properties; and these are accessible on the commercial market. The biggest advantage of FDM technology is the use of plastic materials, for example polylactic acid (PLA), which is obtained from corn, which means that it is a material that supports sustainability. However, there are also some disadvantages of this technology in terms of fine details that are not always printed perfectly. Also, these depend on the printer settings [10,26] as well as economic and sustainability aspects as pointed out in scientific literature [27,28,29,30].

In Section 3, a theoretical and experimental analysis of obtaining gears with different tooth profiles through FDM and vat photopolymerization additive technologies will be carried out. The printing method and the quality of the obtained gears will be considered.

### 3. THEORETICAL AND EXPERIMENTAL ASPECTS REGARDING GEAR PRODUCTION THROUGH ADDITIVE MANUFACTURING

This part of the article summarizes the main stages of creation gears with various geometric features using FDM technology [31,32], but also two techniques from the family of technologies that use as a starting point the raw material in liquid state – LCD and DLP methods. The equipment, the processing programs and the characteristics of the gears resulting from the execution process are also described. In all cases, it started from the CAD model to obtain the three-dimensional model with all geometric and dimensional data, which is then transformed into a file that is compatible with the processing program of the 3D printer. Within the processing program, before the actual printing begins, the designed virtual gear is modeled and sectioned into several successive layers of certain sizes depending on the equipment used and the main working parameters are established - for example, establishing the infill density and pattern, choice of material, layer height, temperature for extrusion device and bed platform, need for sacrificial supports, etc. Then all this information has materialized in another file with the specific format of each printer/3D printing technology and can be sent to the execution. Fig.2 represents the working methodology applied and the principles of operation of FDM and LCD technology for obtaining gears. As can be seen, FDM or thermoplastic extrusion technology implicates melting usually a polymeric filament and transferring it layer by layer on the bed platform to form the final gear accordingly to previously processed information in 3D printer software. In the case of LCD technology, we are talking about a technique from the category of methods that use the raw material in a liquid state (photosensitive resin) with special solidification

properties and it is based on a LCD display that has a role to selectively harden the surface of the liquid resin using UV radiation in order to obtain the final gear with details set in the processing software.

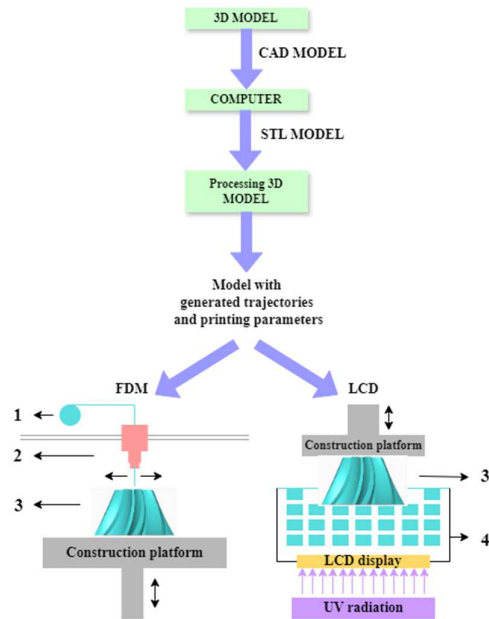
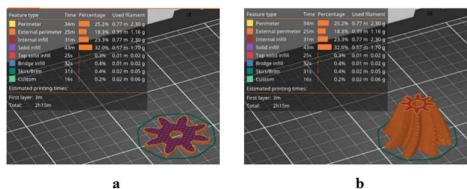


Fig. 2. Methodology and principle of operation for gear production through additive manufacturing (FDM and LCD methods): 1 – Filament; 2 – Extrusion system; 3 – 3D Printed structure of gear; 4 – Vat with photosensitive resin.

In the case of FDM technology, it was considered to exemplify the obtaining of different gears with various profiles and possible uses, namely: cylindrical gear with straight teeth, cylindrical gear with inclined teeth, bevel gear, internal spur gear, chevron gear, rack and nutation bevel gear. In the case of technologies involving the use of liquid raw materials, the execution of the bevel gear was exemplified.

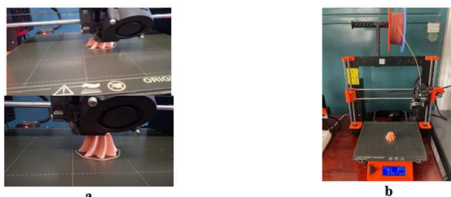
The 3D printer Prusa i3 MK3 was used to materialize the gears through FDM technology, and PLA was used as material, which is known as an eco-friendly material due to its origin (renewable resources such as corn starch or sugar cane). In addition, PLA is considered biodegradable and compostable, having a higher degree of sustainability compared to other thermoplastic materials [33]. Fig.3 shows the interface of the program used for the processing of gears – Prusa Slicer, where the strategy of

using the material can be observed depending on the printing area. Other parameters can be set in this program, such as print settings – layer height, vertical and horizontal shells, details regarding the infill – fill density and fill pattern, details regarding skirt, brim and support material, filament settings – diameter, temperature details for material and bed and so on.

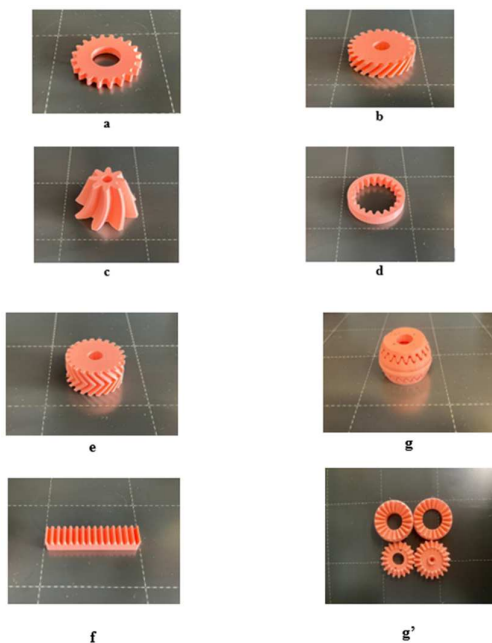


**Fig. 3.** Interface of FDM 3D printing slicer: a – simulation of deposition of first layers; b – finalized structure

Fig.4 shows sequences during the 3D printing of the bevel gear on the Prusa printer.



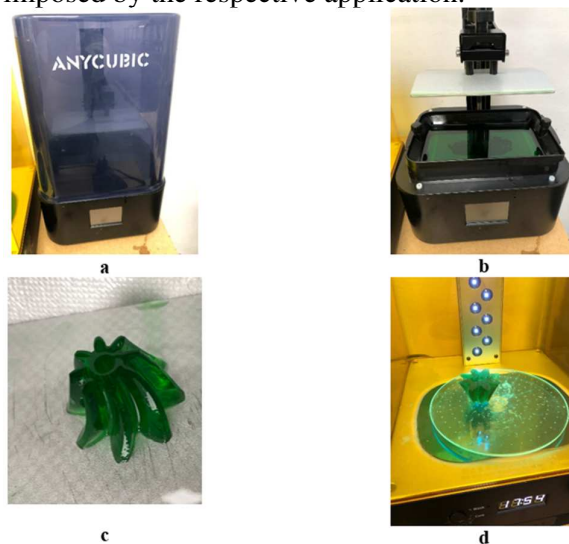
**Fig. 4.** Some details regarding the printing of gears using FDM method: a – gear during printing process; b – finalised gear.



**Fig. 5.** Obtained 3D printed gears through FDM method: a - cylindrical gear with straight teeth; b - cylindrical

gear with inclined teeth; c - bevel gear; d - internal spur gear; e - chevron gear; f – rack; g,g’ - nutation bevel gear

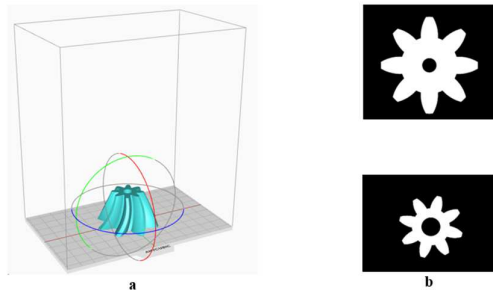
Fig.5 illustrates all the gear elements manufactured using FDM technology. They can be used in various non-demanding applications where a large load is not required for mechatronic and robotic systems, in prototyping applications and other fields. In terms of the applications that target the environment, they can be used in miniaturized or prototypes of water treatment systems, environmental inspection systems or prototypes/models for sustainable devices or machineries, but in this case several factors must be taken into account - such as the physical, chemical and mechanical properties (and other properties of interest) of the material used to fit the technical conditions imposed by the respective application.



**Fig. 6.** Obtained 3D printed gear through LCD method: a, b – 3D printer details; c – obtained gear; d – post-processing (additional photocuring) of the gear

Fig. 6 presents details about the LCD type 3D printer and the bevel gear obtained through this technology starting from a resin with photosensitive properties. In this case, the Anycubic Photon Mono 2 LCD printer and a photocurable resin that hardens under UV radiation with a wavelength of 405 nm were used. After obtaining, post-processing is necessary, i.e. additional photopolymerization in specific equipment to result a gear with final and desired properties (Fig.6d). 3D printing technologies by vat photopolymerization can produce parts with better properties in terms of

dimensional accuracy and resulting smooth surfaces compared to FDM technology. On the other hand, the material used is less friendly to health and the environment, because the resins contain substances that can cause unwanted effects if they are not used properly (use of protective equipment, properly ventilated room, etc), therefore the applications in the field may be more limited.



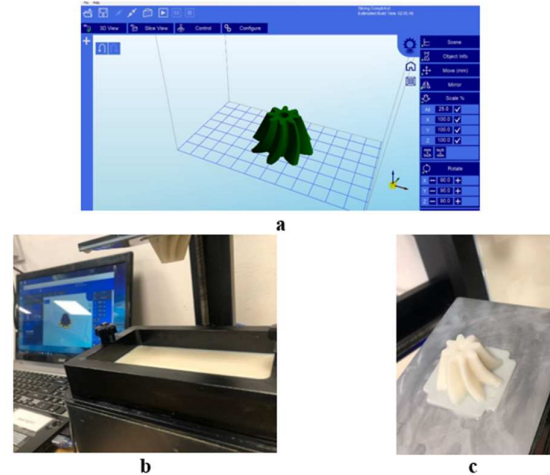
**Fig. 7.** Gear in the LCD printer slicer software: a – gear on the virtual platform of the LCD 3D printer software; b – simulation of layer deposition from the software.

Fig.7 shows the interface of the program used for the processing of gears using LCD 3D printer – Anycubic Photon Workshop software and simulation of layer deposition from the software. In this program it can be set parameters such as layer thickness (50  $\mu\text{m}$  was used), normal exposure time, resin type, positioning of gear on the virtual platform with possible operations of rotating, scaling, mirroring, construction of supports and other characteristics according to needs.

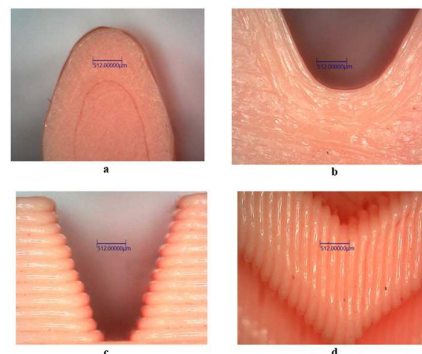
Fig. 8 presents the steps of realization and the final obtained gear by other resin-based technology – DLP using Wanhao Duplicator 3D printer. It is a technology like the previously presented LCD technology, but instead of an LCD screen for processing an entire layer of resin, it uses a complex system (digital light projector) with the key element represented by a digital micromirror device, and the practical difference is given by the method of transmitting the radiation to strengthen the entire layer of resin.

Fig. 9 illustrates microscopic images with the surface characteristics of gears made by FDM technology, namely: tooth of cylindrical gear with straight teeth, bottom of the tooth of the internal spur gear, rack teeth profile and chevron gear profile from which it can be observed the

satisfactory aspect in terms of the quality of the surfaces, but also the layered approach to building the structures used by the additive technology (Fig. 9 c, d).



**Fig. 8.** Obtained 3D printed gear through DLP method: a– gear on the virtual platform of the DLP 3D printer software; b, c – obtained gear.



**Fig. 9.** Some experimental images regarding the obtained FDM 3D printed gears: a – tooth of cylindrical gear with straight teeth; b – bottom of the tooth of the internal spur gear; c – rack teeth profile; d – chevron gear profile.

The work described in this paper falls in line with the one performed in the cited literature. Additive manufacturing techniques for printing enable localized production, cutting transportation emissions and reliance on mass manufacturing. Technology supports the use of biodegradable and recycled materials, such as PLA, which is derived from cornstarch or recycled plastics, further enhancing its ecological benefits [34,35,36]. Moreover, 3D printing contributes to sustainable innovation by extending product life cycles through easy repairs and customization. Industries like

construction and healthcare are leveraging it to create eco-conscious solutions, from low-waste housing to medical prosthetics. As technology advances, 3D printing continues to redefine sustainability in manufacturing and beyond. Additive technology has both positive and negative environmental impacts. On the positive side, it reduces material waste by using only what is needed, enables local production to lower transportation emissions, and supports sustainable materials like biodegradable PLA and recycled plastics. It also facilitates repairability, extending product lifespans. However, challenges include energy consumption, particularly with high-temperature printers, and the environmental impact of non-biodegradable plastic waste. Improper disposal of failed prints and microplastic pollution are concerns [37]. To minimize its footprint, the industry is focusing on energy-efficient printers, sustainable filaments, and recycling programs, making 3D printing a promising but evolving green technology.

#### **4. CONCLUSION**

The novelty of this paper lies in the analysis of additive manufacturing methods for gears fabrication and in the selection of a methodology that enables the achievement of good mechanical properties, which involves sacrificing surface characteristics in favor of significantly improved wear resistance. Following the comparison of the manufacturing methods of these gears, it was concluded that a finite element analysis is required. Based on this analysis, the gear model can be developed and subsequently subjected to metrological evaluations. Additive manufacturing technologies could be employed to provide a sustainable and environmentally aware means of replacing some of the currently used materials in a large array of mechanical devices. A point is made for the further study of such techniques, based on a study of the literature currently available to the authors, with some clear examples identified of steps currently being taken to manufacture materials that could be used to lower the impact on the environment.

Furthermore, these thermoplastic, resins and powders allow for almost zero-waste manufacturing and are a far cry from the material being wasted in producing gears by traditional means. There is also a clear point to be made that typically, the machines used for additive manufacturing consume less power, are less noisy and are overall easier to manufacture and even repurpose. Additive manufacturing, or 3D printing, can be environmentally friendly due to reduced material waste, energy efficiency, localized production, and recyclability of certain materials, mitigating environmental impacts compared to traditional manufacturing. Furthermore, artificial intelligence can promote environmental sustainability through optimized resource management, energy efficiency, predictive analytics for conservation, and automation by reducing carbon footprints in various industries, fostering eco-friendly practices. Using the two technologies together, we could provide a much more economical and eco-friendly future for manufacturers, with less waste, better precision and highly customized parts and mechanisms.

Finally, easy to learn, implement and customize techniques used to design the parts make them easily available to a large population, thus some parts could be replaced without the need for large-scale manufacturing chains as well as pollution caused by the transport industry. Such practices are already being used in a small number of industries but are still largely confined to enthusiasts. Such groups of additive manufacturing enthusiasts embrace innovation, creativity, and sustainability, pushing the boundaries of design and production with 3D printing technologies.

Overall, our study, as well as many others, shows how additive manufacturing technology can be successfully used to allow for both simple and complex mechanical parts and mechanisms to be both created and maintained. Additive manufacturing typically consumes less power compared to classic manufacturing methods due to its layer-by-layer approach, reducing energy-intensive processes like machining and casting. While energy usage varies based on factors like printer type and material, advancements in efficiency make additive manufacturing

increasingly competitive in energy consumption with traditional techniques.

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### **Studiu privind fabricația aditivă ca metodă sustenabilă pentru realizarea roților dințate**

**Rezumat:** Fabricarea aditivă, sau imprimarea 3D, este utilizată la nivel global, realizându-se progrese semnificative în diverse domenii importante, de exemplu în ingineria mecanică și mecatronică. Scopul articolului constă în analiza metodelor de fabricație aditivă a roților dințate, precum și aplicarea acestora pentru obținerea unor mostre de roți dințate, care vor fi analizate atât dimensional, cât și vizual. Au fost comparate diferite tehnologii aditive, cu scopul de a alege varianta optimă astfel încât, pe parcursul procesului de fabricație, mediul să nu fie poluat, imprimanta 3D să nu genereze pierderi de material toxic (reciclabil), dar în același timp să se obțină o transmisie durabilă în timp, care să permită un proces de fabricație rapid și cu costuri relativ reduse.

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