

Study of the efficiency of additive manufacturing for clamping mechanisms in technological equipment

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Abstract

INTRODUCTION: This paper investigates the applicability of modern additive manufacturing (AM) technologies to the production of components for clamping and locating (workholding) devices used in mechanical engineering. Using a modular machine-tool fixture as a case study, the feasibility of replacing metallic parts with engineering polymers, including fiber reinforced grades, manufactured by AM is assessed.

STUDY OBJECT: A two arm workpiece clamping lever was selected for analysis as the most highly loaded element of the fixture used for machining a “crosspiece” part.

METHODS: Based on recommended cutting conditions, the cutting force components were determined, and the required clamping forces were calculated for several scenarios representing a potential reduction in holding capacity (clamping weakening). These loads served as input for strength and stiffness calculations. Equivalent stresses and deflections were evaluated for the baseline steel lever and for alternative designs made from the most common AM polymers.

RESULTS: The study shows that polymer levers with the original geometry do not satisfy allowable stress limits and stiffness requirements. Therefore, the lever geometry was refined by modifying the cross section to achieve the required strength and rigidity under operating loads. Among the materials considered, the optimized lever made from PA6 GF30 provides material savings and lower manufacturing cost while maintaining adequate strength and deformation limits.

CONCLUSIONS: The results confirm the feasibility of using fiber reinforced engineering plastics in additive manufacturing for producing components of clamping and locating fixtures. Further work is required to assess AM fabrication of other, less highly loaded parts and to quantify the influence of print induced anisotropy and process parameters on mechanical performance

Keywords: Levers, Clamping mechanisms; Reinforced plastics; Technological equipment; Force calculations; Design optimization; Additive manufacturing.

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1. Introduction

Driven by recent scientific and technological advances, the mechanical engineering industry is increasingly focused on improving production efficiency and reducing manufacturing costs. Additive manufacturing (AM) offers new opportunities for producing components across a wide range of sectors, including mechanical engineering, aviation, medicine, and construction [1,2]. In mechanical engineering, one key advantage of AM is the ability to fabricate a part directly from a 3D model, reducing the need

for dedicated process planning and conventional machining operations. Another important benefit is the broad range of available materials, as well as the possibility of controlling internal (topological) structures. This enables substantial material savings without a significant loss of functional performance and, consequently, reduces production costs [3,4].

The current limitations of AM—lower dimensional accuracy and surface quality (often requiring post-processing), insufficient stiffness compared with metals for many applications, and the relatively high cost of metal feedstock powders—are being progressively mitigated

through advances in equipment, process control, and material development [5]. These trends suggest potential for expanding AM into domains traditionally dominated by subtractive manufacturing, including the production of machine-tool components and assemblies.

This potential is particularly relevant for modular tooling systems, especially for parts that do not require high dimensional and geometric accuracy and do not affect workpiece positioning accuracy or clamping reliability. Typical examples include clamping–fixture components such as levers, crossbars, spacers, and housings. For such parts, AM enables rapid iteration through parametric CAD models, facilitating fast production of physical prototypes and subsequent fabrication of functional components [4]. As a result, the design cycle can be simplified, component lead time and fixture assembly time can be reduced, and the costs associated with storing blanks and spare parts can be lowered, thereby increasing overall production efficiency.

2. Analysis of Key Achievements and Literature

The development of AM is one of the most actively studied topics in mechanical engineering, and substantial research has focused on improving its technical and economic performance. This is particularly important for small-batch and pilot production, where conventional manufacturing routes may be economically inefficient [1]. For example, study [5] reviews existing AM technologies and identifies directions for further research and process improvement.

Considerable attention has also been paid to the development of new materials for AM [6]. Material selection is a critical factor in AM, especially in applications requiring product customization and tailored performance. Recent studies provide examples of specialized AM materials and discuss their applicability to specific engineering tasks.

One promising direction is the use of polymer composite materials as alternatives to traditional metals in tooling and fixture design [7, 8]. Early work examined reinforced polymers, which attracted industrial interest due to their low density combined with mechanical properties sufficient for use in various machines and mechanisms [9–12].

Mantoux and Bersee [13] extended this line of research by analyzing key mechanical and thermal properties of several composite systems with respect to their suitability for AM. Since these publications, a new generation of advanced composites—many designed specifically for AM—has become commercially available.

For instance, [14] reviews innovative AM materials and discusses the feasibility of selecting materials for specific applications based on properties such as strength, stiffness, and thermal resistance.

Workpiece clamping fixtures are an integral part of machine tooling. In modular fixture systems, components

can be classified into two groups according to manufacturing accuracy requirements: (i) locating elements, which must provide high precision and strength, and (ii) clamping elements, which must ensure durability while typically having less stringent surface and dimensional accuracy requirements [15].

Traditionally, levers, clamps, and similar components are manufactured from steel to achieve high strength and wear resistance, although this approach increases the overall structural weight [16, 17]. Numerous studies indicate that reinforced polymers exhibit physical and mechanical properties that allow them to replace metals in a range of machine components. The use of reinforced polymers can reduce weight by approximately 50–70% while maintaining the required strength characteristics. For example, polyamide PA6 reinforced with 30% glass fiber (PA6 GF30) has been reported to provide favorable performance for mechanical engineering components [12].

Therefore, when designing installation and clamping devices, it is reasonable to identify fixture components that can be transferred from subtractive manufacturing based on metal stock to additive manufacturing using composite materials (e.g., polyamides, thermoplastics, and carbon-fiber-reinforced polymers).

2.1. Aim of the study

This study provides a comprehensive assessment of the feasibility of replacing metal parts in clamping mechanisms for locating and clamping devices with reinforced plastics, and identifies suitable materials and optimal geometric parameters.

To achieve this aim, the following tasks were set:

- analyse the force characteristics that arise in the device during machining of a representative part;
- determine the lever stresses and deflections for different materials, taking into account the actual lever geometry;
- select optimal lever cross-sections for engineering plastic materials used in mechanical engineering, while ensuring functional performance;
- carry out a techno-economic comparison of the considered options.

3. Research materials

3.1. Characteristics of the processing object and basing scheme

The object of the study is the installation and clamping device for a modular machine used to machine the "Cross" part (Fig. 1). The main technical characteristics of the part: material - steel 45; overall dimensions: 80 × 80 × 80 mm. The workpiece has a central through hole of Ø20 mm in the horizontal and vertical directions; the mass of the workpiece is approximately 0.89 kg. The material of the

part is characterized by a tensile strength $[\sigma]_v = 600$ MPa, a yield strength $[\sigma]_t = 360$ MPa, and an elastic modulus $E = 210$ GPa.

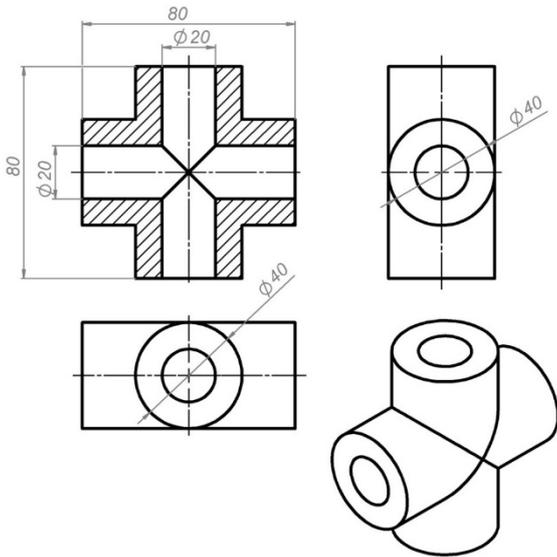


Figure 1. Sketch of the processing object – the "Cross" part

The "Cross" component was chosen as the most common possible mounting option in a fixture when machining on a modular machine. This allows exploration of fixture designs with various mounting arrangements (Fig. 2)

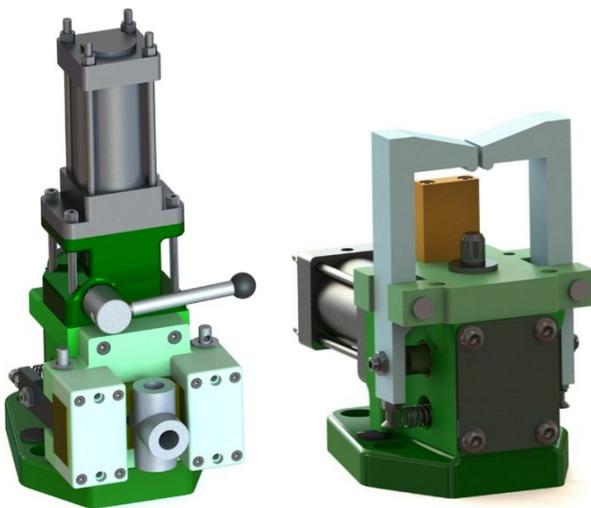


Figure 2. Options for devices for implementing various options for basing the "Cross" part

In this article, we plan to consider only one of these options. We also plan to explore other mounting and clamping options in future research, which will expand the database of standardized elements and parts for installation and clamping devices and examine the feasibility of using

additive manufacturing technologies to produce them. A fixture was chosen for this study.

For this device, basing is performed along one of the ends (3 degrees of freedom) on the support plane and centering along the short finger (2 degrees of freedom); to obtain complete basing, counter sliders with self-centering prisms are used, which deprives the workpiece of the sixth degree of freedom and simultaneously ensures the workpiece is secured (Fig. 3).

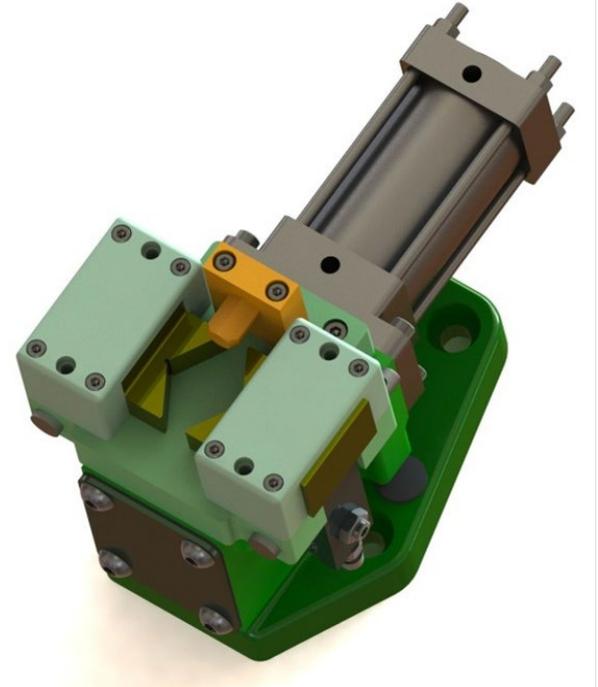


Figure 3. General view of the device

It is obvious that the proposed classical basing scheme and clamping mechanism ensure reliable, fast part fixation during processing and eliminate the possibility of workpiece displacement or tipping.

The workpiece is clamped by two symmetrical prisms, which are secured in sliders connected to levers. The sliders and prisms move symmetrically toward each other. The clamping force from the pneumatic cylinder is transmitted to the levers via a wedge-plunger mechanism with an 8° wedge angle, ensuring self-locking of the device components in the event of a pressure release in the pneumatic system. A spring returns the levers to their original position (Fig. 4).

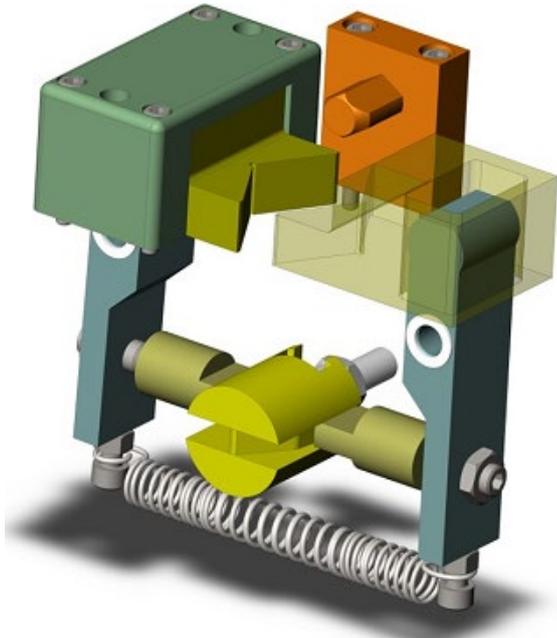


Figure 4. Diagram of fixing a part with lever clamps

When designing the device, the possibility of performing two technological operations on a unit machine was considered:

- drilling of the central hole from $\varnothing 10$ mm to $\varnothing 20$ mm (thickness of the removed layer $a = 5$ mm), tool – CoroDrill Delta - CR840; cutting speed, $v_c = 80$ m/min; feed, $f = 0.1$ mm; diameter, $D = 20$ mm; cutting depth. For these drill designs, the cutting force according to recommendations [12, 13] $P_z = 900$ N; torque $M = 5.8$ N m .

- rough milling of the upper plane with a $\varnothing 63$ mm CoroMill 245-GC4230 end mill to a depth of $a = 1.5$ mm, milling width $B = 40$ mm, cutting speed, $v_c = 150$ m/min; feed per tooth, $f_z = 0.2$ mm; number of teeth, $zn = 5$. For these cutter designs with a plan angle of 45° , an equivalent distribution of the cutting force in the vertical and horizontal planes is characteristic. According to the recommendations [12, 13], for the adopted cutter design, each component of the cutting force is equal to $P_z = P_y = P_x = 800$ N.

3.2. Determining the required workpiece clamping force

The calculation of the required clamping force was performed according to the method [8] taking into account the geometric parameters of the lever: the arm of the clamping part of the lever $l_1 = 36$ mm, the arm receiving the force from the wedge-plunger mechanism $l_2 = 50$ mm, the gear ratio $i = l_2/l_1 = 1.389$ (Fig. 6).

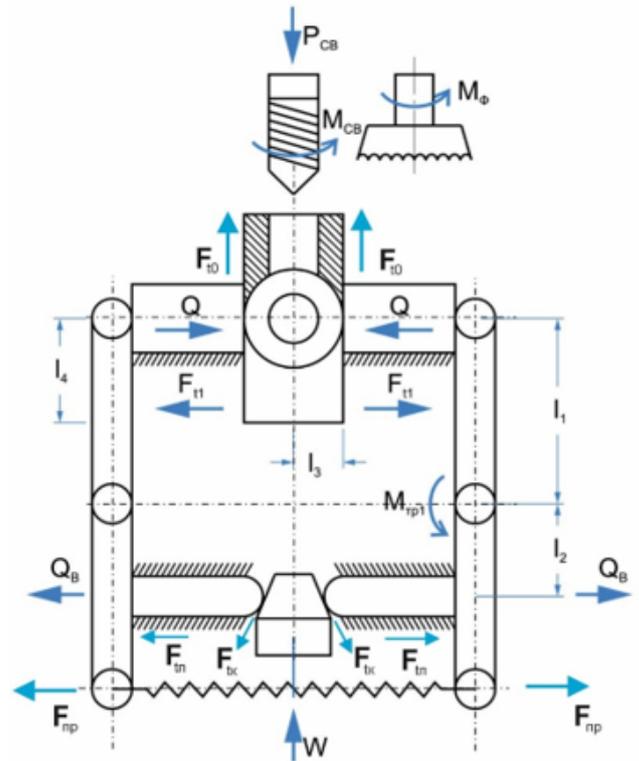


Figure 5. Calculation diagram of the required clamping force

In the calculations, the spring force F_{pr} was considered separately and additionally taken into account, which is necessary to return the levers to their original position when unloading the workpiece.

The safety factor for the performance and reliability of the device k takes into account random factors and is defined as the product of the proportional coefficients:

$$k = k_0 \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot k_6 = 1.3 \cdot 1.2 \cdot 1.4 \cdot 1.2 \cdot 1.0 \cdot 1.0 \cdot 1.2 = 2.5 \quad (1)$$

where $k_0 = 1.3$ is the minimum guaranteed safety factor; $k_1 = 1.1$ takes into account rough machining with a large allowance; $k_2 = 1.2$ is taken into account possible tool wear and an increase in the force load during the machining of a batch of parts; $k_3 = 1.2$ is taken into account the intermittent nature of cutting; $k_4 = 1.0$ is taken into account the type of mechanized drive; $k_5 = 1.0$ is taken into account ease of operation; $k_6 = 1.2$ is taken into account the certainty of the calculation scheme.

Four hypotheses for unfastening the part are considered. Hypothesis #1 (workpiece shift from horizontal force):

Clamping force on each lever

$$Q_1 = \frac{(P_y \cdot k - P_z \cdot f_y)}{2(f_z + f_y)} = 3200 \text{ N} \quad (2)$$

where $f_z = f_y = 0.15$ – friction coefficients.

Hypothesis #2 (workpiece tipping):

Taking into account the clamping arm $l_2 = 36$ mm:

$$M_{o6p} = P_y \cdot h + P_z \cdot b = 96000 \text{ N} \cdot \text{mm} \quad (3)$$

where $h = 80 \text{ mm}$ is the height to the point of application of force P_y , $b = 40 \text{ mm}$ is the distance of force P_z from the center.

Then, the required clamping force is:

$$Q_2 = \frac{(M_{o6p} \cdot k)}{a} = 4800 \text{ N} \quad (4)$$

Hypothesis #3 (separation from supports):

$$Q_3 = P_o \cdot k = 2000 \text{ N} \quad (5)$$

Hypothesis #4 (turn from torque):

$$Q_4 = \frac{(M_{kp} \cdot k)}{(2 \cdot f_3 \cdot R)} = 4833 \text{ N} \quad (6)$$

The required clamping force is determined by the maximum value (per prism):

$$Q = \max(Q_1, Q_2, Q_3, Q_4) = 4833 \text{ N} \quad (7)$$

3.3. Analysis of the clamping mechanism

A lever mechanism with a gear ratio $i = 1.389$ and efficiency $\eta = 0.85$ and taking into account the spring force for unfastening the workpiece requires a drive force of:

The spring force sufficient to return the levers to their original position is determined only by the friction force in the moving parts of the lever mechanism, taking $F_{sp} = 15 \text{ N}$, we obtain

$$F_w = \frac{(Q + F_{sp})}{i \cdot \eta} = 4155 \text{ N} \quad (8)$$

The lever design and its appearance are shown in Figure 6. The lever has two sections of different cross-sections, one connected to the workpiece clamping slider, and the other to the plunger transmitting force from the wedge-plunger mechanism. This is due to the different forces acting on these sections and is based on the design of the device. The lever design is standardized; variants with different section heights H are used (in the calculations, the height $H = 36 \text{ mm}$).

Bending moment for a lever

$$M = Q \cdot l_2 = 241,6 \text{ N} \cdot \text{m} \quad (9)$$

The results of calculating the stresses and deflection of the lever in two critical sections are given in Table 1.

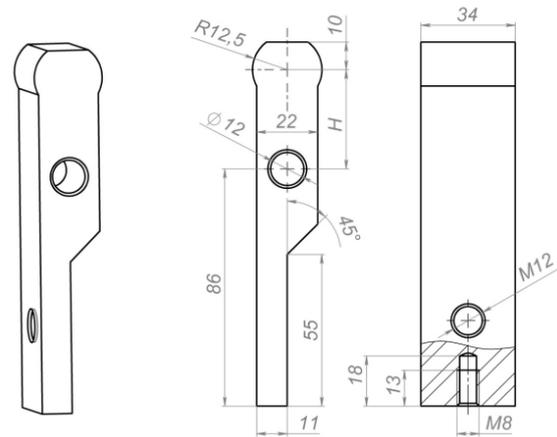


Figure 6. Basic design of the lever

Table 1. Calculated strength characteristics of the lever

Characteristic	Upper section	Lower section
Section, mm	22x34	11x34
Moment of resistance, mm ³	4239	2119
Moment of inertia, mm ⁴	72057	36029
Bending stress, MPa	57	114
Allowable stress, MPa	250	250
Sag, mm	0.006	0.027
Safety margin	4.4	2.2

Thus, a lever made of steel has a significant safety factor ($n > 1.5$) and minimal deflections ($\delta < 0.8 \text{ mm}$), satisfying the operating conditions.

Four materials most commonly used in modern mechanical engineering were considered as alternative materials for additive manufacturing: PA6 (polyamide 6), PA6 GF30 (polyamide 6+30% glass fiber), PA12 GF (reinforced polyamide 12), and PEEK (polyetheretherketone). The main characteristics of the materials are presented in Table 2.

For printing the lever, the largest face (22×132 mm) was selected as the build plate contact surface, and the axis of the lever mounting hole was oriented vertically in the fixture. The extruder deposited the filament along the largest dimension (i.e., the lever height in the selected build orientation). This orientation was chosen to maximize bending strength.

Table 2. Main characteristics of polyamides

Parameter	PA6	PA6 GF30	PA12 GF	PEEK	Steel 45
σ_{in} (MPa)	60	105	80	95	625
E (GPa)	2.0	6.0	3.2	3.8	210
ρ (g/cm ³)	1.12	1.38	1.27	1.3	7.85

T_{max} (°C)	100	140	120	250	300
Moisture absorption (%)	2.0	1.2	1.0	0.1	0.05
Price (€/kg)	80	100	90	500	2

3.4. Comparison of materials and design optimization

In the next step, we calculated the same parameters for the selected materials as for the steel lever. As calculations for the use of polyamides in the study showed, for the considered design of the fixture with a lever clamping mechanism, none of the materials met the operating conditions, as the parts exhibited very large deflections (almost impossible for such dimensions) and an insufficient safety margin (Table 3).

Table 3. Comparative characteristics of the use of reinforced polyamide materials for the existing design of levers

Material	Stock strength	Deflection δ , mm	Suitability
PA6	0.21	12.1	Not suitable
PA6 GF30	0.38	4.20	Not suitable
PA12 GF	0.28	8.10	Not suitable
PEEK	0.33	7.12	Not suitable

Therefore, using ANSYS, lever cross-section options were selected to ensure the required strength and deflection parameters for the device's operating conditions, while accounting for material costs and additive manufacturing expenses. A tetrahedral mesh with 2 mm element sizes was used for the calculation. At the points where the load is applied and transferred to the lever, the mesh size is 1 mm (Fig.7, a). Auxiliary elements—an axle and a pin—were used to secure the lever and apply the load. A "Fixed" joint was used to secure the axle (Fig.7, b). The spring force is represented as the force applied to the pin. A remote constraint along the Z-axis was used to simulate the stop (Fig.7, c). The system of limitations remains the same for the new lever design.

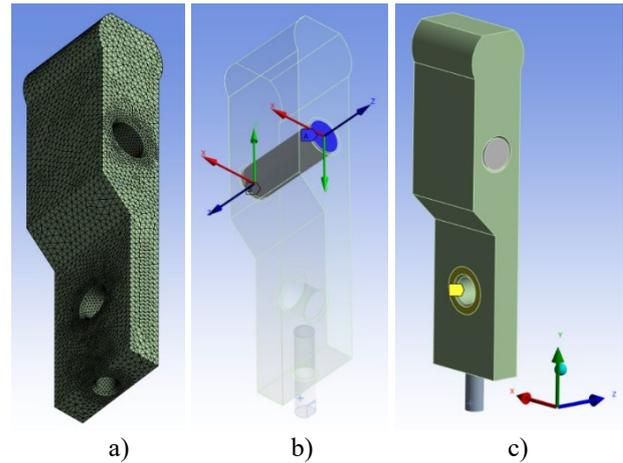


Figure 7. Detailed ANSYS modeling assumptions

The calculation criteria were a safety factor of $n = 1.3$ and a maximum deflection of $\delta = 0.3$ mm, with a minimum strength of 40 MPa. To increase the moments of resistance and inertia while simultaneously reducing the lever's mass, additional design modifications were made: the two stages with different cross-sections were eliminated (i.e., the adopted lever cross-section is the same along its entire length), and stiffeners were used to reduce the component's mass while simultaneously providing a higher moment of resistance. To avoid changing the structural layout of the fixture, a slightly increased lever width was used as a basis, which corresponded to the original drawing (Fig. 8). The use of stiffeners does not require additional operations in additive manufacturing compared to subtractive manufacturing (milling grooves in individual or small-scale production).

A feasibility study was performed in accordance with the recommendations of [20, 21] to estimate the average unit production cost of a set of levers for three attachments of a modular machine (6 parts in total). The cost model accounted for the capital cost of production equipment, depreciation charges associated with equipment payback, labor costs, mandatory social contributions, and additional overhead costs related to plant maintenance.



Figure 8 – New lever design

The analysis considered the following process alternatives:

1. Subtractive manufacturing (machining). Equipment: MILL 850 multifunctional milling machine; assumed payback period: 7 years. Workpiece material: rolled steel bar, 30 x30 mm. The tool type and cutting parameters are specified in the preceding section.

2. Additive manufacturing. For three investigated composite materials (PA6, PA6GF30, PA12GF), parts were produced using a Bambu Lab X1C Carbon 3D printer; assumed payback period: 4 years, for PEEK – Creatbot PEEK-250; assumed payback period: 7 years. The overall dimensions of the printed lever correspond to Table 3. The layer height ensuring the required dimensional accuracy and the recommended process settings was set to $S = 0.05$ mm. The print speed was selected in accordance with the manufacturer's technical documentation for the specified layer height, separately for each material.

The results of selecting the optimal sections for each material are presented in Table 4, and comparative graphs are in Figure 8.

Table 4. Comparative characteristics of optimal lever cross-sections for various materials

Material	PA6	PA6 GF30	PA12 GF	PEEK
Section (mm)	25×35	25×35	25×35	25×27
Area (mm ²)	875	625	750	675
σ , (MPa)	34.5	57.2	45.6	53.1
Stock strenght, n	1.32	1.32	1.32	1.32
Deflection, δ (mm)	0.31	0.22	0.30	0.32
Weight, kg	0.128	0.113	0.124	0.115
Price material, €	10.2	10.11	0.47	57.00
Print time (min)	17	26	24	72
Manufacturing cost, €	12.2	12.89	14.2	65.4

It is obvious that the lever made of PA6 material does not meet the calculation conditions ($\sigma < 40$ MPa), despite having the lowest cost and manufacturing time.

The PA6 GF30 lever (section 25×35 mm) has the smallest area among plastics – 625 mm², a reserve $n = 1.32$ and a deflection of 0.22 mm with a maximum σ value in the best strength indicator (Fig. 8).

A technical and economic comparison shows that manufacturing a lever from PA6 GF30 is the most cost-effective option of the materials considered. Moreover, this option is slightly more cost-effective than manufacturing a lever from steel (12.9 versus 13.5). The service life of PA6 GF30 is 30 000 cycles, which is twice that of PA6 (15 000 cycles). This is sufficient for most industrial applications. PEEK, despite its excellent mechanical properties, is not economically feasible due to its very high cost and printing time. However, in cases where higher surface quality is required, it comes to the fore.

Besides additive manufacturing, additional advantages of reinforced plastics include corrosion resistance, lubrication-free operation, and reduced noise and vibration.

However, they also have disadvantages: a shorter service life than steel, the need for deflection monitoring every 5,000 cycles, and a limited operating temperature (+140° C for PA6 GF30). However, they typically do not exhaust their service life, operate at significantly lower temperatures, and pose no problem during technical preparation of production.

The conducted research demonstrates the use of reinforced polyamides in the production of other device parts for strength and deflection, but requires additional research on wear resistance, especially for parts that create friction pairs.

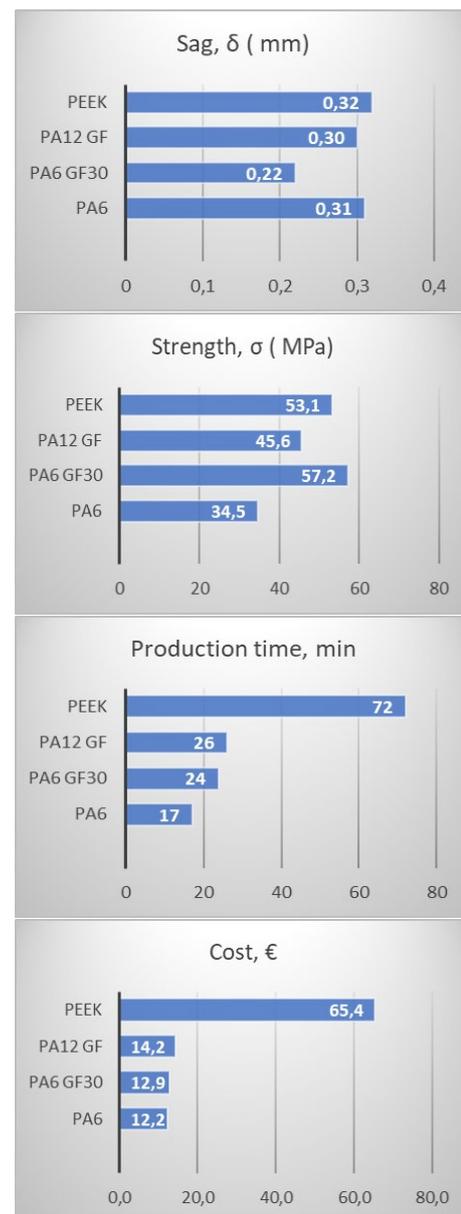


Figure 8 – Comparison of characteristics: stress, deflection, production time, cost for different materials in additive manufacturing of a lever

4. Conclusions

1. A comprehensive analysis was conducted to examine the feasibility of replacing loaded metal components of clamping fixtures with levers made of reinforced plastics. It was found that minor design changes and the assignment of new geometric parameters create favorable conditions for additive manufacturing with plastic materials.

2. PA6 GF30, with a 25x35 mm cross-section, was found to have the smallest cross-sectional area among plastics, while still providing a sufficient safety factor of 1.32. A technical and economic comparison showed that PA6 GF30 provides a weight savings of almost 10 times with a slight cost reduction compared to a steel lever (approximately 5%).

3. Additional advantages of using plastics and additive manufacturing include corrosion resistance, the ability to operate without lubrication, and reduced noise and vibration. A service life of 30 000 cycles is sufficient for most industrial tooling applications.

4. The feasibility of using reinforced plastics, in particular PA6 GF30, in the designs of lever clamping mechanisms of installation and clamping devices to reduce weight, increase cost-effectiveness, and improve some operational characteristics of technological equipment has been proven.

5. Prospects for further research include studying the possibility of manufacturing other, less loaded parts based on additive manufacturing, studying the fatigue strength and wear resistance of reinforced plastics under cyclic loads, and developing a method for optimizing the topology of parts of installation and clamping devices to maximize weight reduction while maintaining strength and functionality

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