Durability of chain transmission obtained using FFF technology*)

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Abstract: Durability of polymer (PCTG, ABS, PLA) chain gears with a modular chain obtained by 3D printing (FFF - Fused Filament Fabrication) was tested under static and dynamic conditions. An analysis was performed using finite element modeling (FEM). The PLA gear showed the highest tensile strength, and the PCTG gear the lowest. However, in dynamic conditions (rotational speed 750 min^{-1}), the ABS gear was characterized by the smallest deformation and the longest operating time. Chain links were damaged at the point of connection during both static and dynamic tensile tests. Probably the surface of the hole where the chain links were joined was not smooth enough, which could lead to their damage.

Keywords: rapid prototyping, flat chain link, additive technologies, PLA, ABS, PCTG.

Wytrzymałość przekładni łańcuchowej wytwarzanej technologią FFF

Streszczenie: W warunkach statycznych i dynamicznych zbadano wytrzymałość na rozciąganie polimerowych (PCTG, ABS, PLA) przekładni łańcuchowych z łańcuchem o budowie modułowej otrzymanych metodą druku 3D. Przeprowadzono analizę metodą modelowania elementów skończonych (MES). Największą wytrzymałość wykazywała przekładnia wykonana z PLA, a najmniejszą z PCTG. Natomiast w warunkach dynamicznych (prędkość obrotowa 750 min^{-1}) przekładnia z ABS charakteryzowała się najmniejszym odkształceniem i najdłuższym czasem pracy. Ogniwa łańcucha zarówno podczas statycznych, jak i dynamicznych testów rozciągania ulegały uszkodzeniu w miejscu ich łączenia. Prawdopodobnie powierzchnia otworu w miejscu łączenia ogniw łańcucha nie była wystarczająco gładka, co mogło prowadzić do ich uszkodzenia.

Słowa kluczowe: szybkie prototypowanie, łańcuch z płaskimi łączeniami, technologie przyrostowe, PLA, ABS, PCTG.

Chain drives serve to bridge the gap between gear drives and belt drives due to their reliability, resistance to external factors (such as moisture, contaminants, and temperature changes), ability to operate without slippage, ease of installation, and relatively low maintenance [1, 2]. They are widely used in machinery manufacturing [3]. Given the advantages of chain drives and their wide application, a study was conducted on the durability of a modular chain produced using additive technologies. Solutions most like the one discussed in the article are segmented V-belts, often made of wear-resistant composite materials. Their benefits include the ability to compensate for assembly errors, quick repairs, and ease of assembly due to the possibility of joining with additional elements [4]. However, they have disadvantages such as a shorter chain lifespan, reduced tension, and elongation due to traction, periodic deformation, and varying friction in the contact area, leading to increased vibration, temperature, and slip [5, 6]. Furthermore, Chen G. *et al.* [6] concluded in their research that the friction of belts, including the segmented V-belt, increases under dry and cold conditions. Another solution like the one discussed in the article is a flat chain conveyor, most often used for transporting light products, mainly in the food industry [8]. The benefits of the flat chain conveyor include its versatility and the ability to be individually configured as per requirements [8]. The literature does not provide information on the widespread use of chains made from plastics. Peng K. *et al.* [9] studied the ability to dampen shocks and regulate wave propagation through

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a cylindrical shell chain with different density distribution. Its structure was inspired by structures found in nature, such as inside of the bamboo, grass stems, and horse hooves. However, its application differs from the discussed chain.

Material extrusion (MEX) technologies are rapidly developing due to their congruence with widely used thermoplastic polymers in commerce, ease of implementation, and general availability [10, 11]. Hence, they are increasingly used in commercial, research, and hobby sectors for manufacturing machine components and developing functional engineering prototypes and systems [12, 13]. One of the advantages of rapid prototyping (RP) technologies (including MEX, which forms the basis for some 3D printing technologies) is their high flexibility [14]. This allows for the creation of parts with reduced weight, designed using topology optimization, enabling the creation of porous internal structures. Moreover, to create lightweight elements, internal structures can be accessed in software designed for preparing parts for printing, specific to the prototyping device [15].

Considering the lack of research on chains produced by RP technology and the growing interest and use of additive technologies in industry and academia, an analysis using the finite element method (FEM) was undertaken. Also, bench tests were conducted on a chain drive produced using fused filament fabrication (FFF) technology and the PrusaSlicer 2.4.1 software. Choosing to produce a segmented chain was due to the search for a practical application of machine elements produced using rapid prototyping techniques. FFF technology was selected due to its availability, thermoplastic materials with diverse properties [16], competitive prices offered by device manufacturers compared to other devices using different additive technologies, and the possibility of producing the analyzed chain drive [10, 17].

EXPERIMENTAL PART

Materials

Glycol modified poly(cyclohexylenedimethylene terephthalate) (PCTG), acrylonitrile butadiene styrene copolymer (ABS MG94) and poly(lactic acid) (PLA) were supplied by Essentium (Pflugerville, Texas, USA). Table 1 lists the mechanical properties of the polymers with respect to the orientation of the tested sample relative to the bed of the prototype device and the arrangement of the fibers.

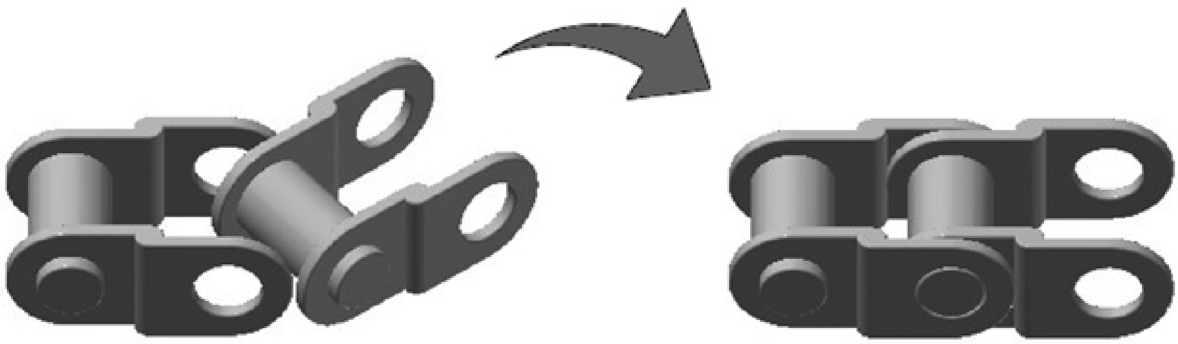


Fig. 1. Diagram of chain link connection

T a b l e 1. Mechanical properties of PLA, ABS, PCTG and PLA based on the data sheets

Polymer / Property	ABS MG94 in print orientation: XY/YX/ZX test method	PCTG in print orientation: XY/YX/ZX test method	PLA in print orientation: XY/YX/ZX test method
Ultimate tensile strength, MPa	37.1/32.7/27.2 ISO 527-2	44.0/43.5/45.0 ISO 527-2	61/51/43 ASTM D638
Tensile modulus, GPa	2.34/2.31/2.24 ISO 527-2	1.81/1.72/1.86 ISO 527-2	3.39/3.17/2.82 ASTM D638
Elongation at break, %	4.5/3.8/1.5 ISO 527-2	130/4.9/3.9 ISO 527-2	*no data*
Flexural strength, MPa	67.5/54.5/47.6 ISO 178	72.7/63.1/71.5 ISO 178	105/64/73 ASTM D790
Flexural modulus, GPa	2.37/2.23/2.17 ISO 178	1.78/1.57/1.72 ISO 178	3.17/2.31/2.70 ASTM D790
Notched Izod impact strength, kJ/m^2	17.0/4.3/3.3 ISO 180	7.5/6.1/4.7 ISO 180/A	31/40/40 ASTM D256
Specific gravity, g/cm^3	1.04 ISO 1183	1.23 ASTM D792	1.24 ASTM D792

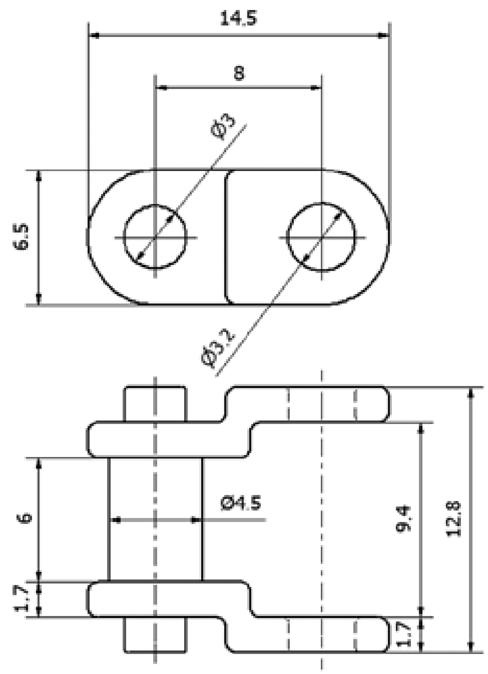


Fig. 2. Assumed dimensions of chain links in mm

XY orientation means that the sample lies flat on the build platform and the individual fibers are aligned along the sample. The YX orientation is like the XY orientation, but the individual fibers are aligned across the sample. ZX orientation means that the test sample is placed perpendicular to the build platform. The tensile strength test pads were produced using a Prusa Mini+ printer (Prusa Research a.s., Prague, Czech Republic).

Chain design solution concept and model 3D

A concept for a single-row modular chain was developed, with its modularity based on a design consisting of individual, snapping links (Fig. 1). The implemented solution facilitates assembly and replacement of a damaged link, as is the case with widely used segmented V-belts and flat chains [3, 8].

Additionally, due to the applied FFF incremental technology, it was noted that the critical parameter is the wall thickness of the links. Therefore, considering the diameter of the standard nozzle (d_{sz}) and the width of the material path it makes (w_s = 0.42 mm), it was assumed that the wall thickness is 1.7 mm. Furthermore, to minimize the production time of a single link, it was assumed that a single link should occupy up to 2.5 cm^2 on the working platform (s_o), which is why an 8 mm chain pitch (p) was used. Based on these assumptions, the geometry of a single chain was designed, as shown in Figure 2. Additionally, the total degree of filling of the printed links was applied and the layer height (h_w) was set to 0.1 mm.

Using the design accelerator module in Autodesk Inventor 2023 (Autodesk, San Rafael, California, USA), sprockets and a chain were designed. Due to bench limitations related to the maximum axis spacing, the number of teeth on the drive sprocket was set to 19, while the driven sprocket was set to 57. The number of chain links based on the entered data was set to 38, and then it was verified that the distance between the centers of the sprockets was 65.5 mm. Finally, the sprocket hubs were modified to adapt them for durability analysis. The chain drive completed model is shown in Figure 3.

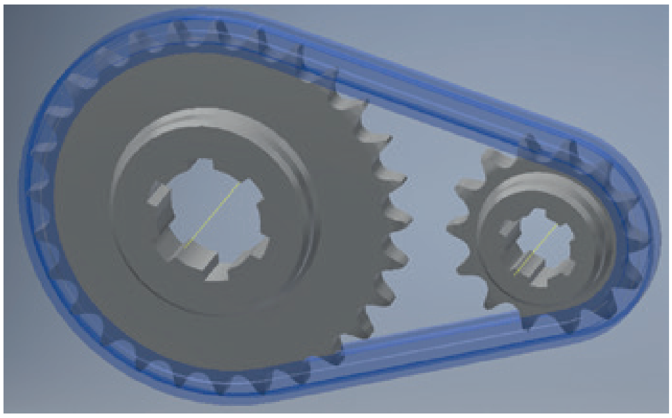


Fig. 3. Completed chain transmission model

FEM analysis

After preliminary tests and ensuring that the design would fulfill its purpose, part of the chain drive assembly was subjected to strength analysis using FEM in the Autodesk Nastran environment. An assembly was created consisting of sprocket and several chain links section, which were connected using specific contacts (Fig. 4). PC-ABS material was selected for the sprocket segment, and PCTG with the lowest mechanical strength for the chain segment. The last chain link not in contact with the wheel was blocked (Fig. 5a), as was the cylindrical surface of the chain wheel hub (Fig. 5b), to which a torque of 2.5 Nm was applied (Fig. 5c). Finally, a mesh with a single element size of 0.4 mm was generated over the entire device. Figure 6 shows the von Mises stress distribution for the entire assembly.

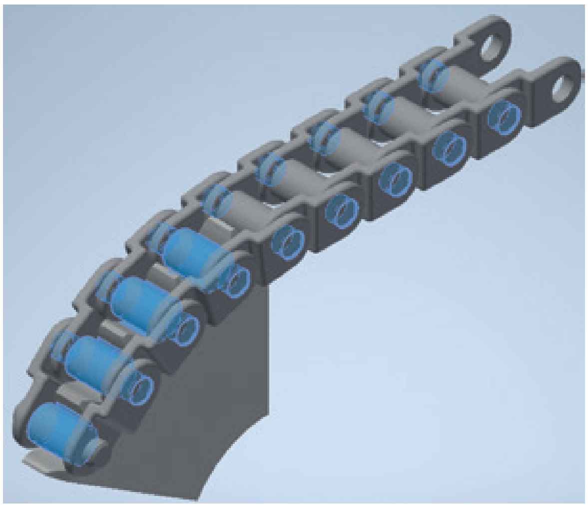
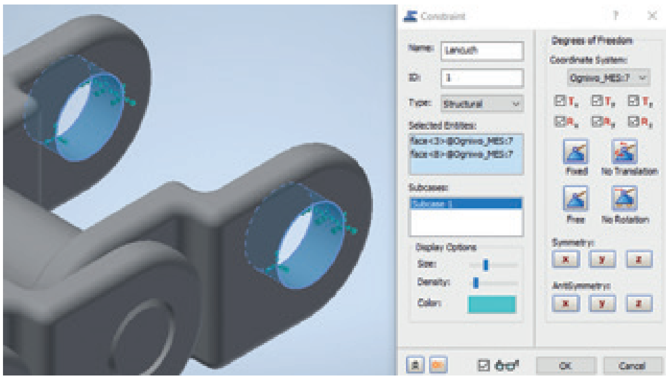


Fig. 4. The unit for performing FEM analysis

a)



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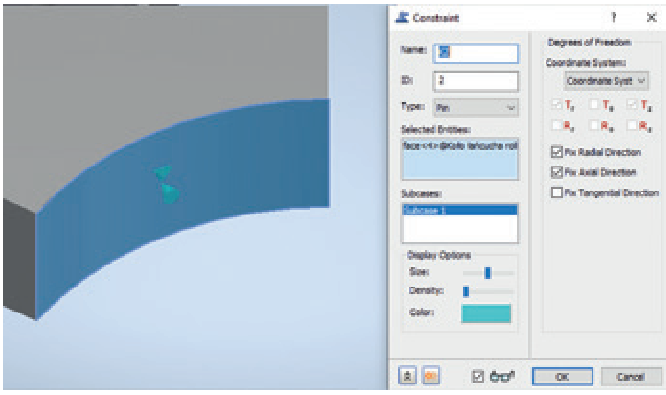

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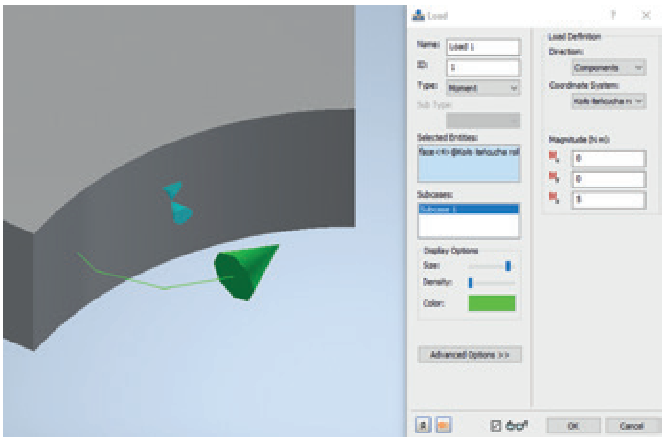


Fig. 5. Boundary conditions: a) chain, b) sprocket, c) torque added to the chain wheel

Chain transmission prototype manufacturing using FFF technology

Based on the chain drive sprockets model shown in Figure 3 and the chain link shown in Figure 2 and the assumptions made, prototypes were made from the tested materials. The head and build platform temperatures were set in accordance with the settings for the given material in PrusaSlicer 2.4.1. Figure 7a) shows a preview of the generated file, while Figure 7b) shows the process of printing links from PLA. Additionally, Figure 8 shows the PCTG chain transmission.

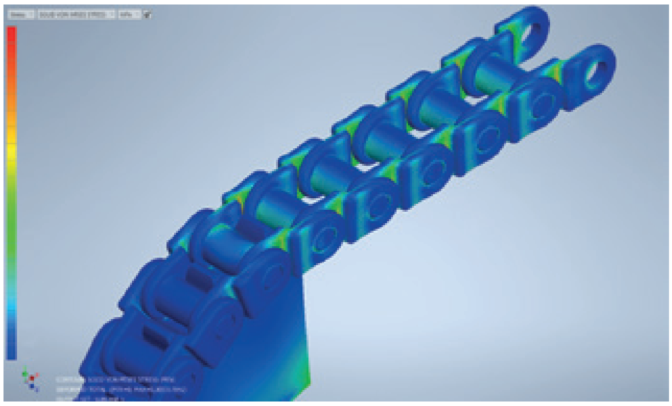
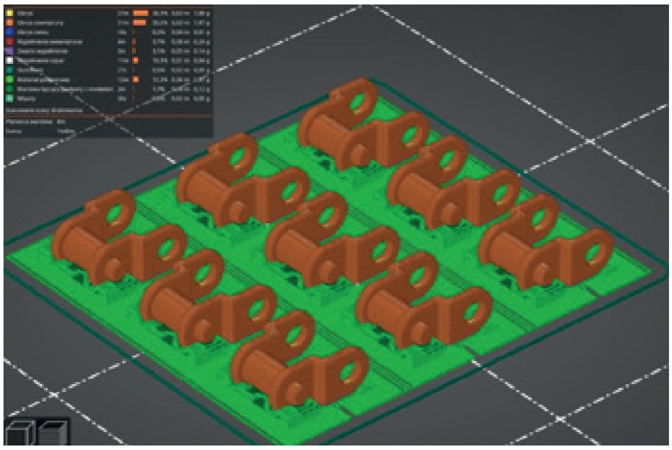


Fig. 6. Von Mises stress distribution after static analysis of the chain transmission assembly element

Static tensile properties

Static tensile properties were performed on the Mecmesin MultiTest-2.5i apparatus (Slinfold, West Sussex, UK) at a crosshead speed of 2 mm/min in accordance with the PN-EN ISO 527-2 standard (Fig. 9). Fig. 9b) shows a chain attached in the testing machine.

a)



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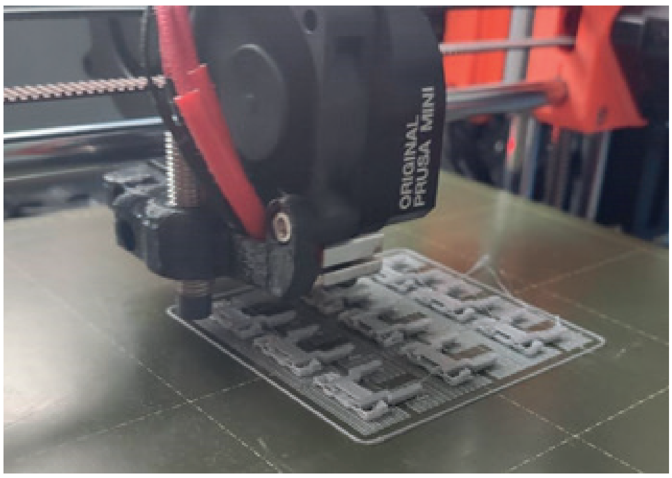


Fig. 7. Chain links cut into layers (a) and printing process using FFF technology (b)

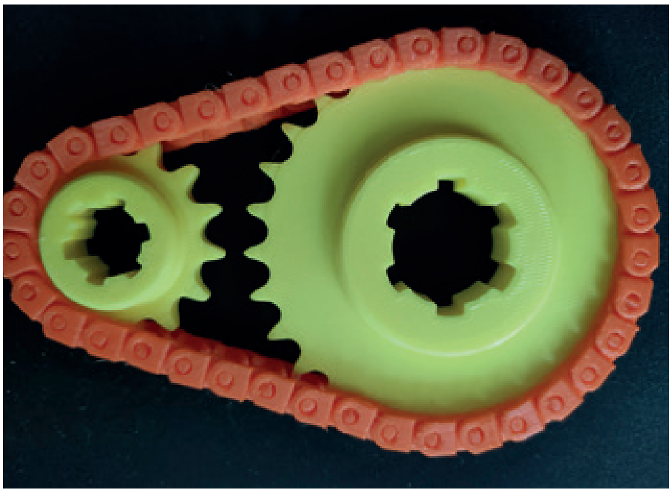


Fig. 8. Chain gear model

Dynamic tests of polymer chain transmission

To check the chain's resistance to dynamic loads occurring during operation, the chain drive tests were carried out at the transmission control station (Fig. 10). For each type of material, the chain was placed on the sprockets and pre-tensioned. The chain was then subjected to load cycles in the form of a braking torque applied to the input shaft. A single cycle lasted 120 s, and the braking torque increased by 1 Nm at the end of each cycle, starting from 1 Nm. At the same time, temperature and sound intensity were measured in relation to the background (Fig. 11). After preliminary tests of the gearbox, the rotation speed of 750 rpm was assumed.

Sound level pressure testing

During dynamic tests of polymer chain transmission, sound levels were tested using CEM DT-95 (CEM, Shenzhen, China) simultaneously, as can be seen in Figure 11.

RESULTS AND DISCUSSION

Tensile properties

Based on the tests performed (Table 2), it was found that PCTG has the lowest tensile strength (33.7 MPa), and PLA has the highest (48.8 MPa). Regardless of the sample and material, due to internal stresses caused by the static tensile test, the chain cracked around the hole for the pin in the smallest section, characteristics of which indicate brittle fracture (Fig. 9c). Only for ABS chain, color changes were noticed around the crack, which may be related to the degradation of polymer chains, occurring during the plastic tension stage (Fig. 9d). Because chain links were damaged in different spots, cross-section of every part was different, tensile strength calculated according to various cross-section area was impossible to compare. For this reason, it is better to compare tensile force required to break the chain (Tab. 2).

T a b l e 2. Properties of the polymers used, and the chains made of them

Property	Sample	PCTG	ABS	PLA
Tensile strength, MPa	Specimen	33.7	40.7	48.8
Tensile force, N	Chain	138.3	180.6	238.0
Sound pressure, dBA	Chain	92.4	93.1	92.3

Dynamic tests of polymer chain transmission

Dynamic tests of closed chains were carried out at the gear inspection station. Figures 12a)–c) show the stretching of the chain made of PLA, ABS and PCTG after

a) b) c) d)

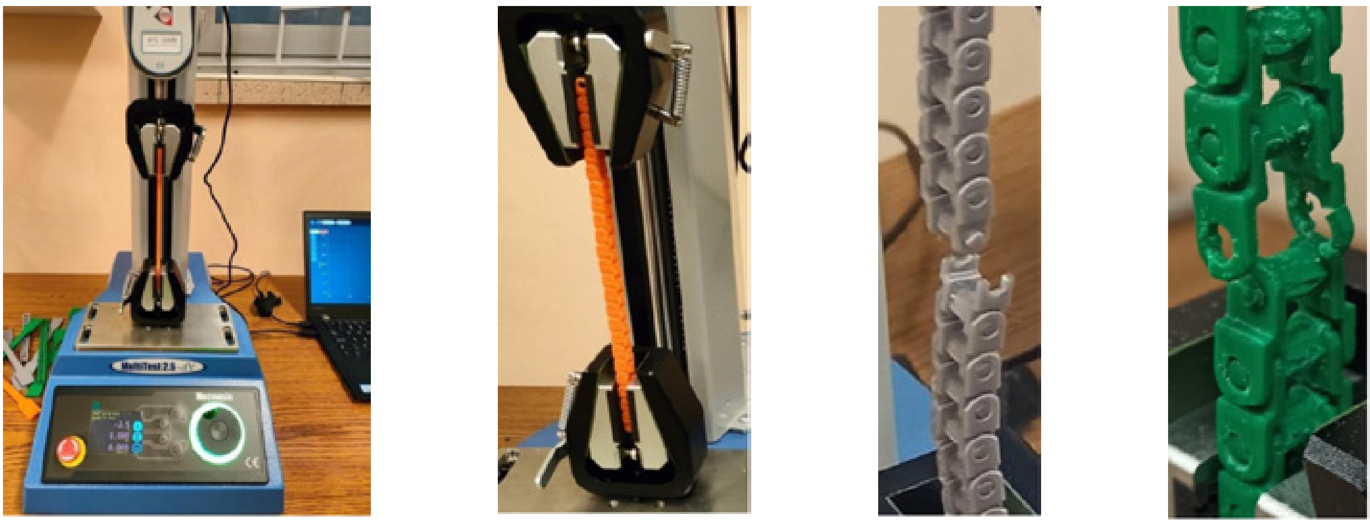


Fig. 9. Static tensile testing apparatus (a), attached PCTG chain sample (b), damaged PLA chain sample (c), and damaged ABS chain sample (d)

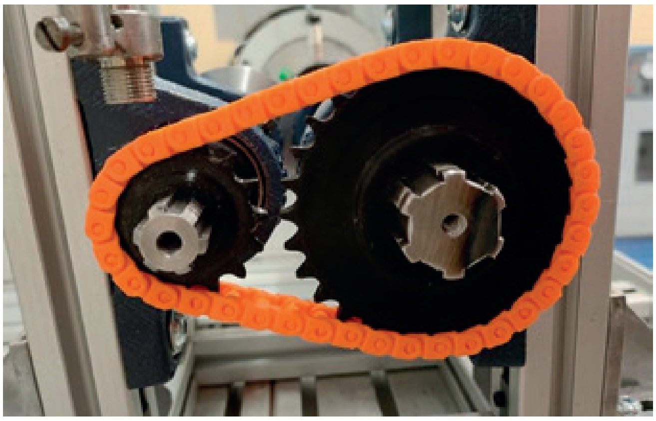


Fig. 10. PCTG chain assembled on a gear testing machine

approximately 30 s. The moment of PCTG chain destruction is shown in Figure 12d).

The end of the cycle during the dynamic test of the chain transmission occurred when the chain was suddenly damaged by breaking a link at the weakest part of the construction (Figs. 12d and 13). The chain's stretch after the test was significantly greater than before, as illustrated by the example of PLA and PCTG chains (Fig. 13). This phenomenon is caused by wear of the pin connection in all links. The fit has changed from tight to lose (the "stepped" connection surface of the connecting pin has worn out). The PLA chain broke after 10 s when the load was increased to 2 Nm (Fig. 14a), and the PCTG chain broke when the torque was increased to 4 Nm

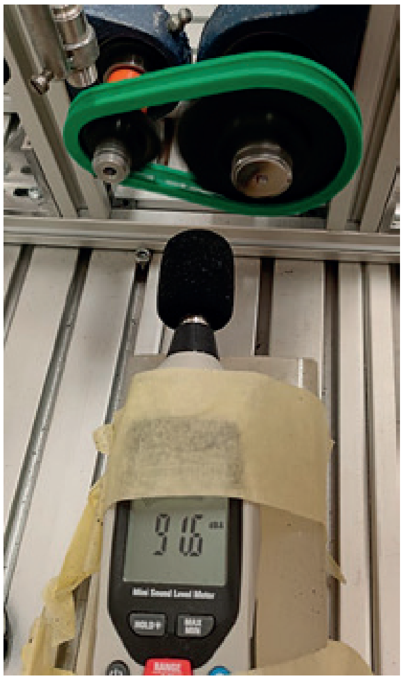
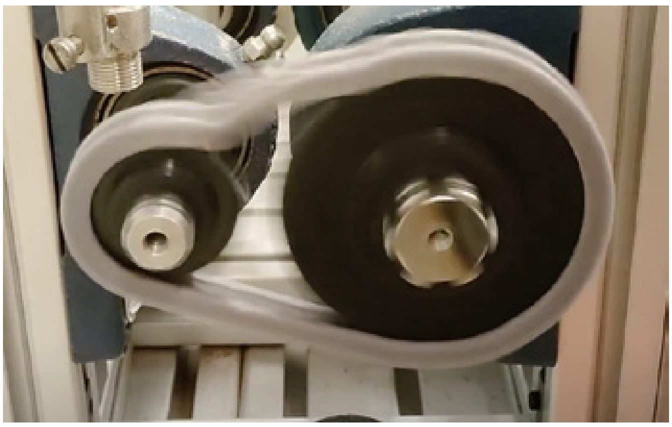


Fig. 11. Dynamic tests of ABS chain on a gear testing machine

a)



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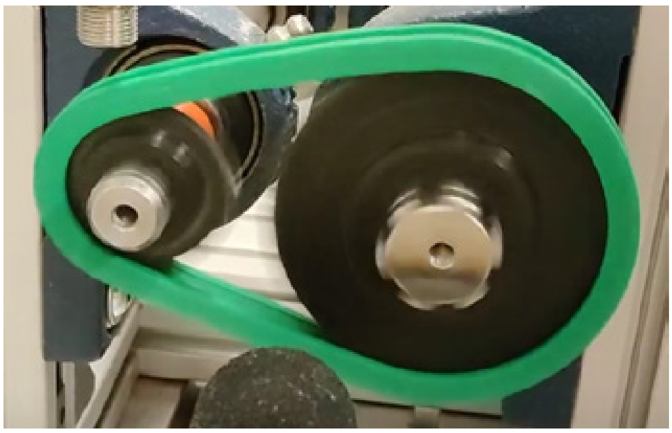
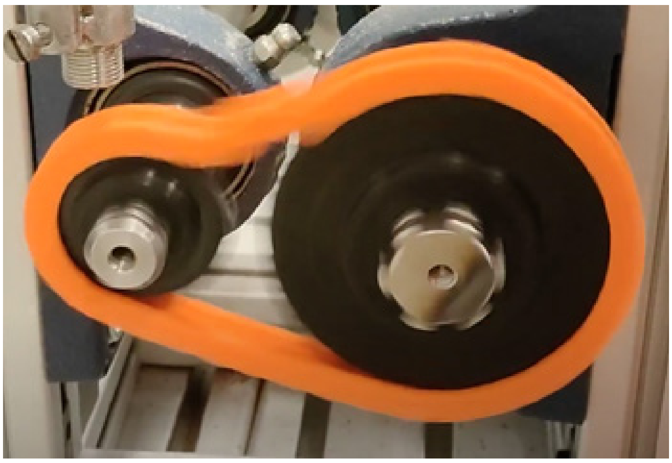


c)



d)

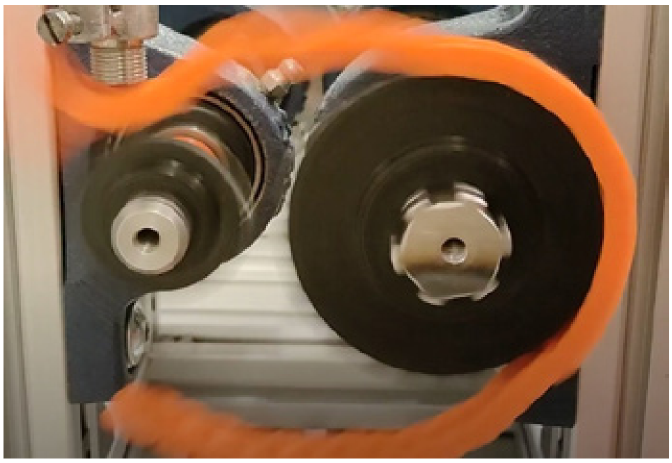


Fig. 12. Dynamic test: a) PLA, b) ABS, c) PCTG chain after 30 s, d) destruction of PCTG chain

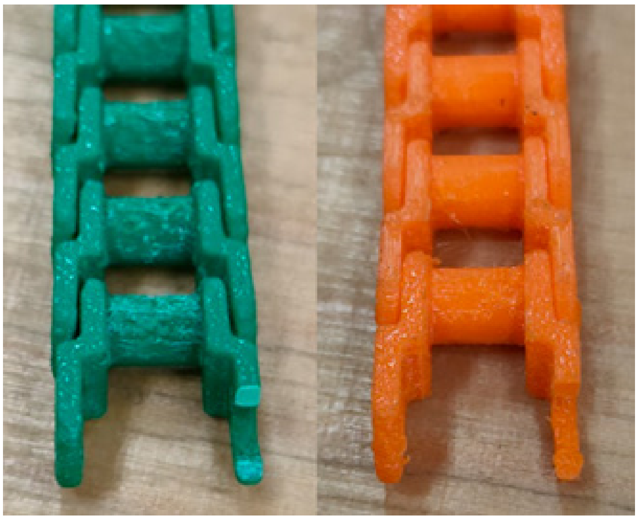


Fig. 13. The nature of damage to chain links made of ABS (green) and PCTG (orange)

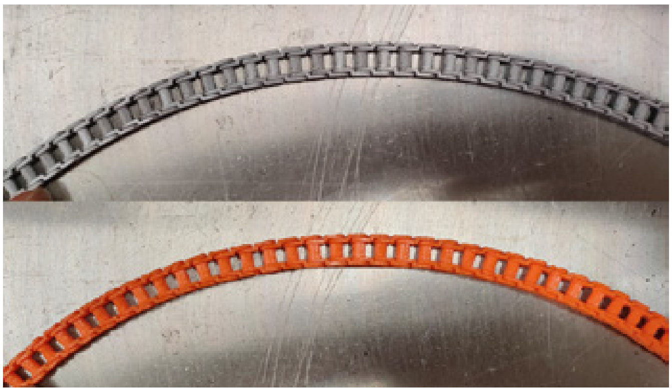


Fig. 14. Stretching chain made from PLA (grey) and PCTG (orange) polymers after dynamic tests

(Fig. 12c, d). Moreover, the ABS chain was destroyed after approximately 30 s when operating under a load of 4 Nm (Fig. 12b). It was also observed that during operation of the PLA and PCTG chains, their elongation occurred almost immediately after the start of the test (Fig. 14).

Sound level pressure

The sound pressure differed slightly between the tested polymers (Tab. 2). During operation, the ABS chain reached the highest pressure (91.3 dBA). Due to the short operating time of the chain, which in the case of ABS chain was the longest (approximately 30 s), temperature was omitted in the research, considering its impact to be too short to affect the results.

CONCLUSIONS

The tested chains made of three different polymers (PLA, PCTG and ABS) showed high durability in both static and dynamic tests. The PLA chain had the highest tensile strength, and the PCTG chain had the lowest. The ABS chain, which at the same time had the smallest stretch among the tested chains, worked for about 30 s under a load of 4 Nm, until to damage. Meanwhile, the chain made of PCTG worked for about 10 s at a load of 2 Nm until it broke. The chain made of PLA was destroyed only when the torque was increased to 4 Nm. The nature of chain link damage during the dynamic test is the same as during the static tensile test - the links were damaged at the opening point. Chains made of PLA and PCTG showed a similar tendency to stretch. The weakest chain element was the link at the point of the smallest cross-section. This is related to the additive technology used, which, despite high precision in the form of the smallest layer height offered by the software and adapting the dimensions of the cell to the printing nozzle used, resulted in the hole shape not being round and its surface being jagged. The position of the cells relative to the working platform also influenced the quality of the hole surfaces, which did not contribute to maintaining a round cross-section. Therefore, the nature of the link hole surfaces can generate unexpected forces as the chain wraps around the sprockets, which can lead to link damage. It was also noticed that the concentration of von Mises stresses in the chain and sprocket segment does not correspond to the damage of the links during the discussed tests, which may also be related to the geometry of the link due to the technology used.

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