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CONTRIBUTIONS ON GEARS MANUFACTURING FOR PRECESSIONAL TRANSMISSIONS BY INJECTION MOULDING AND ADDITIVE METHODS

Alexandru BUGA, Alina BREGNOVA

Abstract: *The choice of the manufacturing method of plastic gears presents a great challenge for technologists. Therefore, it's needs to do an extensive study on the materials and the choice of the manufacturing method taking into account the quality, the environment and the purpose of use of the precessional transmissions (PT) and not least the manufacturing price. This article provides theoretical and experimental contributions on fabrication of PT gears by two methods: molding injection and additive methods. Engineering plastics of interest are researched and highlighted. Manufacturing techniques and machinery. The technological particularities regarding to improvement of the mechanical properties, the quality of the parts and minimize the coefficient of friction between gear wheels. Gear design procedure for PT. At the end of the work are presented a comparative analysis of the proposed manufacturing processes.*
Key words: *precessional transmissions, gear wheels, injection molding, additive method, engineering plastics.*

1. INTRODUCTION

Plastic gears are increasingly used in car mechatronic systems, technological equipment and machinery, household appliances, aerospace, etc. Thermoplastics used as replacement materials in steel gears due to technical and economic advantages. Compared to metal gears [1], the advantages of polymer gears are: low specific weight [2], no maintenance required [3], high resistance to wear in a dry environment (self-lubricating) [4], low noise [5]; vibration damping [6]; corrosion resistance; resistant to chemical solvents [7]; high inertial moment and reduced mass [8]; cheap production [9], possibility of recycling. And the disadvantages are presented in the form of: it requires increased attention on the operating temperature [10], lower mechanical and thermal properties compared to ferrous and non-ferrous materials [11], low manufacturing tolerances [12].

Due to the appearance on the market of electric motors (12V D.C) of high speed (approx. 10,000 RPM) with reduced dimensions and mass, mechanical transmissions with a high transmission ratio are increasingly being asked. The use of involute cylindrical gears to obtain high transmission ratios requires the manufacture of a complex gear of large dimensions and high price.

It is good to note that harmonic transmissi-ons have a limited lifespan, especially the flexible wheel has a lifespan of no more than 5000 hours.

Therefore, it is necessary to manufacture a simple gear with fewer moving and fixed elements at a low price, in order to achieve the right transmission ratio. Precessional transmissions (PT) are composed of only four functional elements: satellite wheel (3), movable wheel (2) and crank axle (6), fixed wheel (1) that ensures a transmission ratio of up to 1/5000, fig.1. Unlike in planetary transmissions, the same ratio is executed by 28 functional elements and same in the harmonic ones. For the manufacture of the functional elements of the PT by mold and additive methods it is it is necessary to respect the constructive and functional particularities of the gear: a) the satellite has two rows of teeth with circular arc profile (Z2 and Z3) that geared with the fixed wheel Z1 and the movable wheel Z4, b) the satellite carries out the sphero-spatial motion in fixed point C of the intersection of the generators; c) in the PT, several pairs of teeth are engaged simultaneously; d) between teeth exist sliding friction, which leads to temperature increase, [14].

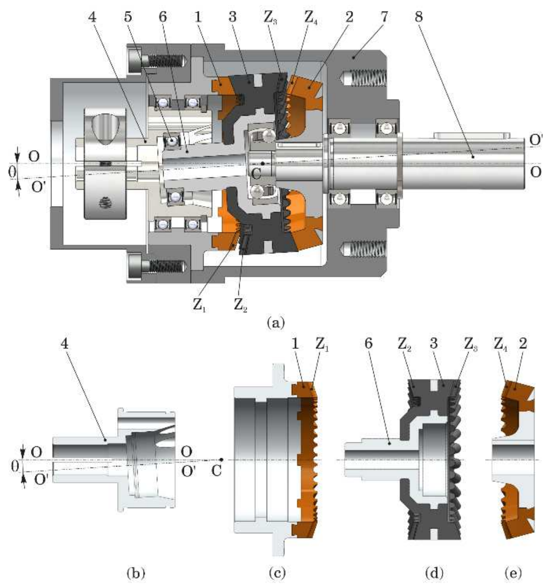

Fig. 1 Presentation of the functional elements of the precessional reducer a) the axial section of the PT; b) crank; c) fixed wheel; d) the satellite from POM with axle from aluminum for heat release; e) movable wheel, [13]

During the design of PT, it is necessary to pay more attention to improve the heat release from the gear, because the end melting temperature of thermoplastics are low, fig.2 (for POM is 1850C and for PA66 is 2700C). For the design and manufacture PT gears by the methods mentioned above, an important role is played by the correct choice of material, to ensure: a) the precise formation of the contact geometry; b) reducing and excluding residual stresses; c) efficient evacuation of heat from the contact area of the geared teeth; d) highlighting technological requirements of the injection molding and 3D printing process; e) reducing the production cost.

2. SELECTION OF THE THERMO-PLASTIC POLYMERS FOR PT MANUFACTURING.

Unlike metallic alloys that are Euclidean rigid with linear Hookean behavior thermoplastics are real fluid bodies with Maxwellean behavior. Thermoplastics are viscoelastic bodies that under the action of force, the viscoelastic body "flows" but also deforms elastically. In other words, under the action of external forces, thermoplastics possess a rheological compartment from the point of view of the ratio between the relaxation time and the time of the material called the Deborah number [15]. When designing thermoplastic gears, it is necessary to know the rheological deformations, thus a body (solid or fluid, from now it's thermoplastics), unlike steels, depending on the mechanical demands can have the following states of aggregation: elastic solid, viscoelastic solid, viscoelastic fluid, viscous fluid. The problem of deformation interconditioning, representing the totality of the regrouping phenomena at the atom molecular and supramolecular level, as a way of interrupting the continuity in a tense body, it's particular interest for explaining the mechanical properties of thermoplastics, as well as for clarifying the causes that trigger the primary act. The application of an external force field on a polymer, triggers a structural reaction, which is located at the molecular or supramolecular level depending on the intensity of the stress and the presence of defects that focus the elastic energy. The deformation of complex structures, of the nature of polymers, consists of a sequence of specific phenomena, from elastic to viscous behavior.

When choosing thermoplastic polymers for PT, must be taken into account the primary factor regarding vulnerability to high temperatures of polymers, which is formed in the friction-slip contact area between teeth.

Fig.2 shows the maximum operating temperature of thermoplastics, for POM is 1500C and for PA66 is approx. 200 ^{0}C. At those temperatures between teeth exist a fluid film.

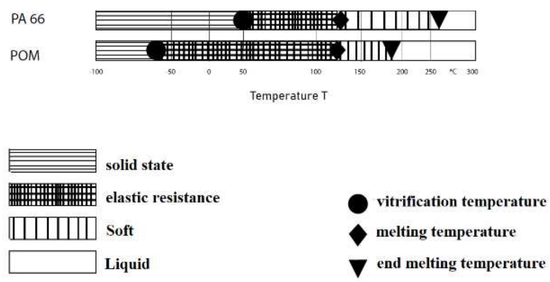

Fig. 2. The state domains of thermoplastic polymerized materials, [16].

Steps must be taken to remove the heat from the contact area between the teeth. Also, must be taken into account the coefficient of friction between the active surfaces of the parts.

Tab. 1.

Wear coefficients of involute gears

Gear materials	Wear coefficient	Torque (Nm)	Load cycles ($x10^{5)}$
POM/PA6	1.3	9.8	1.28
POM/POM	0.15	8	2
PA66 30 GF15PTFE/ PA66 30 GF 15PTFE	0.1	5	1.2
PA6 30GF 15PTFE 2 Si/ PA6	0.2	0.8	1.3
PA66 30 GF 15PTFE2Si/ POM 20 PTFE	0.7	0.8	1.6
PA66+30GF PTFE15Si2/ PA66+30GF PTFE15 Si2	0.5	0.6	1.8

Around the world was done conformist and non-conformist experimental researches regarding the selection of optimal pairs of thermoplastic materials for gears, especially for involute ones. Pure and composite thermoplastics were highlighted. Unsaturated polyester resins as nylon (PA6) and (PA66), polyacetals (POM) [17], polyphenylene sulfide (PPS), polyether ether ketone (PEEK) [7] and polybenzimidazole (PBI), which are used in pure and composite state (carbon fiber (CF) or glass fiber (GF) reinforced, polytetrafluoro-ethylene (PTFE) used for dry lubrication of gears, etc.), [18]. N.A. Wright and N. Kukureka, [19] researched the wear coefficient at different torques and obtained wear coefficients of involute gears, tab1.

Jože Tavcar et all ingeniously calculated the friction coefficient between different polymers, tab.2.

Tab. 2.

The friction coefficient calculated based on the temperature released from the gears, [20].

Gear materials	μ - friction coefficient
PA6 – PA6	0.53
PA6+30GF–PA6	0.45
PA6+30GF–POM+10GF	0.34
POM+20PTFE–PA6	0.29
POM–PA6	0.29
PA66+20PTFE–POM	0.29
POM+10GF–PA6	0.29
PA66+20PTFE–PA6	0.27
PA66+30GF/15/2–POM	0.27
PPS+30CF/15–POM+20PTFE	0.25
PA66+30GF/15/2–PA6	0.23
PA66+30GF/15/2–POM+20PTFE	0.22
PPS+30CF/15–POM	0.22
PA66+30GF/15/2–POM+10GF	0.22
PA66+30GF/15/2–PA66+30GF/15/2	0.21

The results of the studies have differences, but practically all researchers mentioned that the primary influence on polymer gears is the temperature and the time of use, two factors that contribute to wear. The appearance of temperature is due to friction, namely the sliding/rolling effect of the gear. Many defects occur due to material erosion, high moments and insufficient heat transfer. The wear depends on the type of reinforcement of the material and the orientation of the fibers, in the direction of rolling the wheel wears less but the location of the fibers perpendicular to the direction of rolling, the wheel wears more. It is important to research the wear path of thermoplastic materials and their thermal resistance. The addition of reinforcing materials in thermoplastics helps to strengthen the surface, which will lead to the improvement of the tribological behavior of the polymer. This reduces wear and decreases the coefficient of friction in dry conditions.

3. PARTICULARITIES OF THE PT'S DESIGN

For the design and manufacture of kinematic precession transmissions [13], it is necessary to prepare a calculation algorithm, which includes the constructive and kinematic features, including the geometry of the contact and the new principle of transmission of movement and load.

3.1. Specifications

As a rule, the specification is drawn up by the beneficiary, in which functional and constructive parameters are specified (torque, gear ratio, RPM of the electric engine, weight and dimensions, maximum permissible load, impact, stiffness, lifetime, mode of operation (continuous or intermittently), the maximum temperature and environment of use, opaque or transparent, defining highly productive or unique manufacturing processes (mold fabrication, 3D printing, mechanical processing), the availability and accessibility of the thermoplastic material, cost of manufacturing PT gears.

3.2. The PT gear design stages

The argumentation of the kinematic structure consists in the choice of the kinematic structure, for example the 2K-H type which includes two central gears, the satellite and the crank shaft. Gear ratio 144:1, it must be taken into account that the input and output shafts rotate in the opposite direction, [21].

Tab. 3.

Configuration of the number of teeth of the wheels and the gear ratio,[21]

Z_1	22	26	**29**	32	35	38	43	45
Z_2	23	27	**30**	33	36	39	44	46
Z_3	28	23	**25**	27	29	31	34	35
Z_4	19	22	**24**	26	28	30	33	34
*i**	-114	-148	**-144**	-143	-144	-146,3	-145,2	-142,2

* Note - the input and output shafts rotate in the opposite direction.

The material chosen by the beneficiary is POM whose mechanical and technological properties are indicated in the table below, tab.4.

Tab.4.

The properties of POM from RTP Co., [22]

Permanence	Measurement units Metric (SI)
Specific gravity	1.41
Moulding shrinkage (3.2 mm section)	1.70%...2.90%
Mechanical	
Impact strength, izod: notched (3.2mm section) unnotched (3.2mm sec.)	80 J/m 1495 J/m
Tensile strength	60 MPa
Tensile elongation	>10%
Tensile modulus	2413 MPa
Flexural strength	76 MPa
Flexural modulus	2413 MPa
Electrical	
Dielectric strength	19.7 kV/mm
Thermal	
Ignition resistance	1.5 mm
General processing for injection molding	
Injection pressure	69-103 MPa
Melt temperature	182...218 ^{0}C
Mold temperature	79...107 ^{0}C
Drying	2 hours -121 ^{0}C
Moisture Content	0.15%
Dew point	-32 ^{0}C

The case and cover can be made by the 3D printing method.

3.3. Pre-dimensioning and preventive design.

PT calculation and pre-dimensioning is carried out according to the algorithm presented in table 7.3 [14] pages 44-45. The CAD, CAE and CAM design is recommended to be done in the dedicated software from Dassault System or Autodesk, fig.3…fig.5, [23].

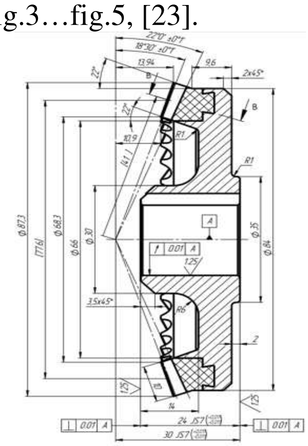

Fig.3. Movable wheel of PT [14].

The functional elements of the PT type 2K-H are the satellite and the mobile and fixed wheels, these elements require increased attention in manufacturing, what concerns the generation of teeth. It good to mentioned that to fabricate mold forms (positions 19 and 21 fig.10) need precise machining, [14]. In this way, all the constructive elements of PT are designed to obtain the general assembly, fig.7.

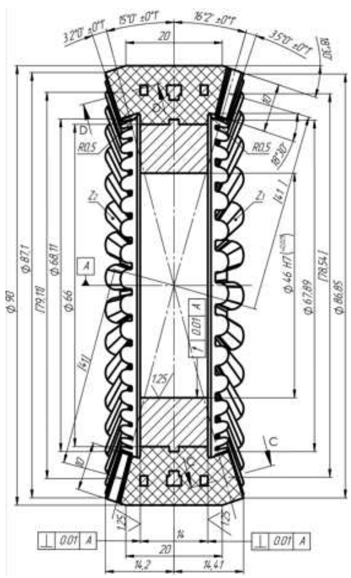

Fig.4. The technical drawing of the satellite with two toothed crowns.

The rotational movement of the crank shaft (10) installed in bearings (11) turns into precessional movement of satellite (2) through the bearing (9) mounted on the axis of the satellite (7), fig.7.

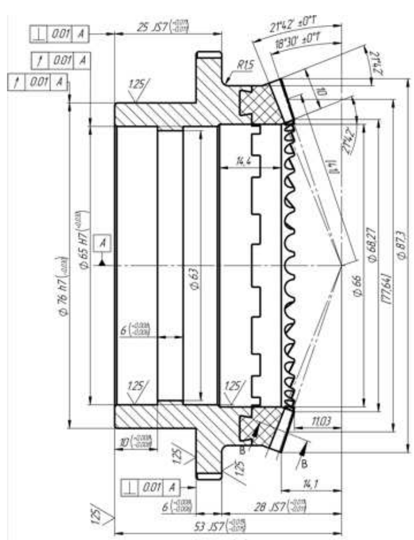

Fig. 5. The technical drawing of the PT's fixed wheel

Teeth Z2 and Z3 of the satellite wheel (2) engages with teeth Z1 of the fixed wheel (3) and Z4 of movable wheel (4), fig.7, thus making the rotation movement with the transmission ratio:

$$i = \frac{-Z_2}{Z_4 * (Z_1 Z_3 - Z_2 Z_4)} \quad (1)$$

Fig.6. PT's elements fabricated by mold injection, [14]

In the fig.6 are presented main functional elements of the PT, fabricated by mold injection. For injection was used PPA 30CF PTFE15 thermoplastic, [24].

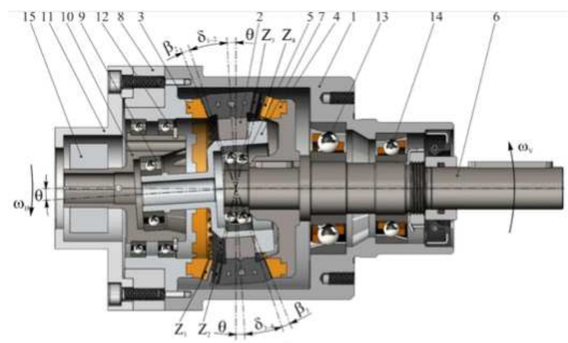

Fig.7. Sectional view of PT,[24]

In the fig. 7 are presented the constructive simplicity of PT that contains only three elements, (fig.6), which participate to transmission of gear ratio: the satellite (4) and two gears (6), (7) that can be assembled using robot or cobot.

3.4. PT manufacturing

For the manufacture PT gears was designed and made the injection mold, fig.8. The ingenious construction offers the possibility of producing different satellite, fixed and mobile wheels by changing the mold form (19) and (21), fig.8. The negative profile of the forms 19 and 21 were processed by electro erosion with the filiform electrode, fig.9, [24].

The regimes and conditions of the injection process for each type of material, tab.2, are recommended by the thermoplastic's manufacturer, for example tab.4. In order to obtain quality parts, the adjustment of regimes that differ a little from those mentioned by the manufacturer was observed through the empirical method.

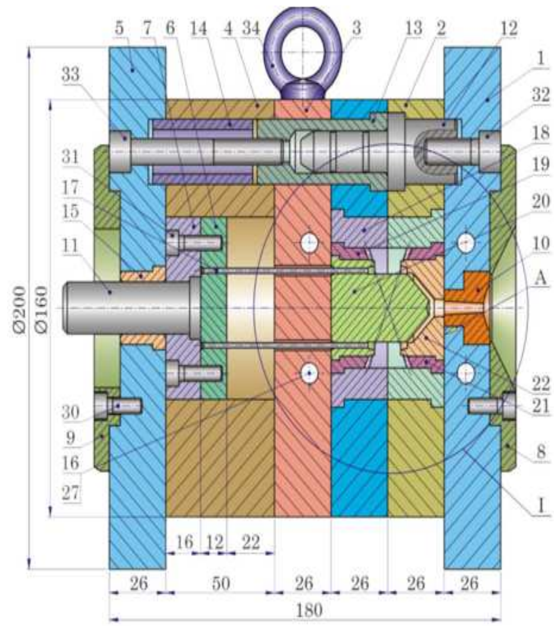

Fig.8. Sectional view of the injection mold, [24].

Injection mold consists of three parts: the fixed part, the forming part and the movable part. The fixed part is made up of the base plate 5 with the guide bush 15. The piston 11 that activates the ejectors 17 to release the piece.

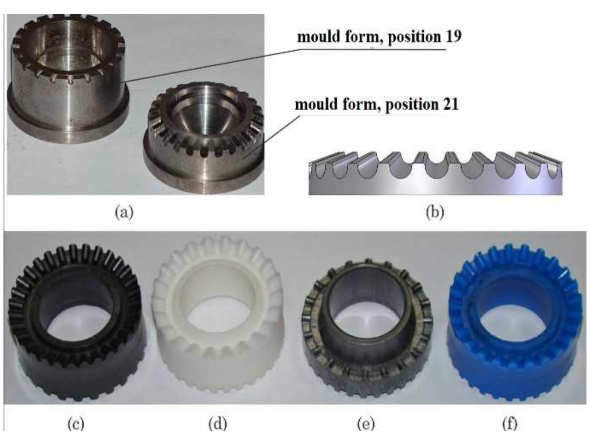

Fig.9. Mold form for injection the satellite a), the 3D model of the mold form b), the satellites obtained from POM polymer c) and d), from nylon PA66 e) and f),[24].

The forming part is made up of pressure plate 3, on which are located the inserts 18 and 19, the supports for the molds 19 and 21. Inserts 18 and 22 are mounted in the movable part, between them are located mold 21. On the movable plate 1 located injection nozzle 10.

4. THE PT MANUFACTURING BY ADDITIVE METHOD

PT are innovative products and have not yet manifested themselves as free products on the market, so the economic aspect of sales, transportation, commissioning, installation, etc., are not yet specified. However, the already well known functional-constructive features denote that PT successfully compete economically with other transmissions, and in some cases can replace them permanently.

Rapid prototyping technologies are in the focus of research for many authors these days. One of the main manufacturing technologies for rapid prototyping is additive manufacturing, especially fused deposition modelling (FDM), which is used in this research for manufacturing of planetary gearbox prototype. Machines for FDM have low cost and they become available for regular people out of the universities and big companies. Detail reviews about rapid prototyping and additive manufacturing can be found in papers [26,27].

The evolution of additive manufacturing (AM) over the past three decades has been a real short of extraordinary. The AM market has grown hundreds of times for 18 of the last 27 years, starting from a promising set of non-commercialized technologies in the early 1980s and growing to a market worth more than $14 billion [28,29]. The AM market has grown to more than $21 billion by 2020. This growth has been made possible by improvements of AM materials and technologies and is driven by market drivers that require its use, such as: shorter product development cycles, increased demand for customized and personal products, increased focus and regulations on durability, reduced manufacturing cost, etc.

Below 4 PT gears were examined and studied which were manufactured with the same geometry but different printers, material depending on the printer used and the position of the gear during printing.

At Technical University of Poznan, from Poland, was opportunity to experience the printing of precession wheels on the latest generation 3D printers. Printing process was done on two 3D printers Epsilon W50 and ZORTAX M200 and was used two different printing regimes, thus for the Epsilon W50 printer 2 wheels were printed in the vertical position at an angle of 15° – one with a full shell and another with holes. Also was printed the same wheel with the same geometry horizontally on the ZORTAX M200 printer.

The choice of printer is an important point in gear printing. BCN3D Epsilon W50 SC - powerful professional independent dual extruder (IDEX) 3D printer designed to create solid, large parts from industrial grade materials with a heated chamber and fully enclosed housing. The Epsilon W50 has a fully enclosed chamber with a controlled internal temperature that can reach 60°C and the platform itself up to 120°. It has all the features to create medium quality gears. The Zortrax M200 is a semi-professional desktop printer made in Poland, equipped with an extruder and a heated platform. The minimum thickness of the applied layer is 100 microns.

Due to the self-calibration of the platform, the extruder with three heating elements and the optimized software architecture, the device has a high print quality, [14]. Below are arranged their parameters in a table, so that the difference is visible, namely the power of both printers.

Tab. 5.

The printers parameters [30,31]

Parameters	Epsilon W50	Zortrax M200
3D Printing Technology	FDM (Fused deposition modeling)	FDM (Fused deposition modeling)
Dimensions	420x300x400 mm	200x200x180mm
Number of extruders	2 pieces	1 pieces
Extruder max. temperature	300° C	290° C
Heated bed	max. 120°C	max. 105° C
Noddle diameters	0.2, 0.3, 0.4mm	0.4 mm
Materials	ABS	(PS) HIPS
Print time of satellites	11 h	9 h

Tab. 6.

Properties of ABS and PS materials respectively [31,32]

Material properties	ABS	PS
Filament diameters	2,85 mm	1,75 mm
Extruder temperature	210-245°C	210-245°C
Melting temperature	175°C	175°C
Layer thickness	0,1 – 0,2mm	0,1 – 0,2mm
Material density	1,04g/cm^3	1.136 g/cm^3
Hardness	97 Mpa	73.2 Mpa
Tensile modulus	2300 MPa	--
Tensile Strength	22 Mpa	16,4 Mpa

Rigid models with snap-fit joints [31]. Was printed 2 wheels in the vertical position from ABS material and horizontal position from polymer Z-HIPS (PS) to observe the quality of the teeth surfaces. An important step is to study the properties of the materials used in printing, especially when it comes to gear wheels. Important criteria for choosing the material is the admissible temperature for long-term operation and heat resistance [35].

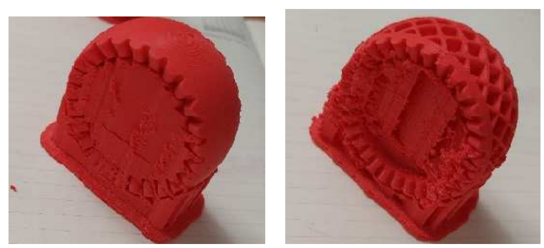

Fig.10 A, B Presentation of two PT gear models printed on the BCN3D Epsilon W50 SC printer.

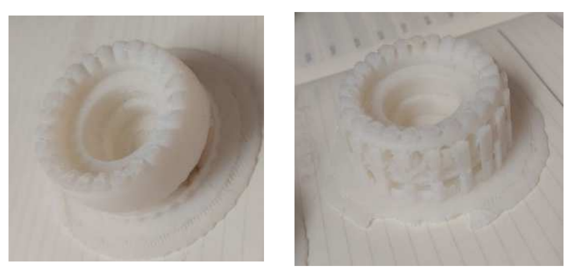

Fig.11. A, B The satellites printed on The Zortrax M200

Although in this work was studied how well the same wheel was printed on different printers, and diverse material.

PS is a versatile thermoplastic perfect for 3D printing prototypes that can be used in thorough testing before production processes begin.

Fig. 10 and fig. 11 shows samples of precession gear satellites with multipair convex-concave contact of teeth manufactured by Additive Technologies, 3D printing in different periods.

5. RESULTS AND DISCUSSION

Following the execution of the parts by the additive manufacturing and mold injection methods, the surface roughness of the active parts of the teeth were measured. For surface roughness measurement was used Taylor Hubson Form Talysurf Series 50 mm Intra System no. FTSI-6742.

Tab. 7. The surface roughness of the active parts of the teeth of gear obtained by mold injection and 3D printing.

Gear's material	Mold injection	3D printing
POM	0.3 μm	1.8 μm
PA66	0.5 μm	2.1 μm
ABS	0.3 μm	2 μm
PA66 30GF	0.6 μm	-
PA66+30GF	0.5 μm	-
POM+10GF	0.9 μm	-
POM	0.5 μm	-
POM 20 PTFE	0.7 μm	-
PPS	1.2 μm	-
PS	1.1 2 μm	2,3 μm

About 3D printing some points should mention: horizontally printed gears have a much worse quality than vertically printed gears.

The Zortax and Epsilon printers are high quality printers with good detail. Analyzing the parameters of these printers and especially the examples of the printed objects, the printed gears are quite accurate, but the printing of the PT gears are different because the construction of the gear is different.

Manufacturing of the PT wheels PT in a vertical position, under an angle of 15 degrees gave gears of a better quality than the gears manufactured in a horizontal position. A tooth break was observed when printing horizontally, which was not the case when printing the wheel in a vertical position.

The gears of the precesionale transmission are different from the usual gears and their construction does not allow us to get a final necessary result for the improvement of the transmissions. But the rapid step of development of the additive methods, I believe will make this possible in the near future.

6. AKNOWLWDGMENTS

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Information about mobility to access here: https://www.ceepus.info/

7. CONCLUSION

This article provides information on thermoplastic materials used for manufacturing by additive and mold injection methods of PT, tab.1. The friction coefficients between the involute cylindrical wheels are shown in tab. 2. Design features and the calculation of the PT transmission ratio. The manufacturing process by mold injection and mold construction. During mold injection, the injection regimens were highlighted, which are a little different from those given by the RTP supplier for POM injection, chapter 3.5.

- Is clear that the wheel injection method is more expensive in terms of manufacturing the matrix, but instead, we have a good result.
- It is easy to notice major differences between the roughness of the parts, tab.7, the surface quality is better.
- Pieces obtained by mold injection take on the roughness of the mold forms fig.9, position 19 and 21. Unlike, pieces obtained

by the additive method whose roughness depends on the size of the deposition nozzle diameter, and on the additive method and other parameters.

- The manufacturing of wheels with non-standard profile through additive technologies are under developing, having as object increasing the execution precision, dimensions and surface quality.
- At the moment there are no professional printers that could print gears with the required quality, but new technologies continue to surprise us with new opportunities, so we just have to search.
- In the near future we will print a few more examples on other new printers for better teeth quality and good gear meshing.
- However, we tend to look for new state-of-the-art printers for faster and cheaper manufacturing because the injection method remains expensive and time-consuming compared to the additive method.

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Contribuții privind fabricarea roților dințate pentru transmisii precesioanle prin injectare în matrice și metoda aditivă

Alegerea metodei de fabricare a roților dințate din mase plastice prezintă o mare provocare pentru inginerii tehnologi. Prin urmare, este nevoie de a face un studiu amplu privind materialele și alegerea metodei de fabricație ținând cont de calitatea, mediul și scopul utilizării a TP și nu în ultimul rând prețul de fabricație. Acest articol aduce contribuții teoretice și experimentale privind fabricarea de roți dințate pentru TP prin doua metode: injectarea în matrice și metoda aditivă. Se cercetează și se evidențiază materialele plastice inginerești de interes. Tehnici și utilaje de fabricație. Particularitățile tehnologice privind îmbunătățirea proprietăților mecanice, calității pieselor și a minimizării coeficientului de frecare dintre rotile dințate angrenate. Procedeul de proiectare a roților dințate pentru TP. Ca rezultat, la finele lucrării se prezintă o analiză comparativă a procedeelor de fabricație propuse .

Alexandru BUGA, PhD, Vice dean, Technical University of Moldova, Department of Machine Design, , Str. Studentilor 9/8, alexandru.buga@precesia.utm.md
Alina BREGNOVA, PhD student, Technical University of Moldova, Chisinau, Magda Isanos 5 street, alina.bregnova@gmail.com