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DESIGN WITH USE OF 3D PRINTING TECHNOLOGY

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Abstract:
Dynamic development of 3D printing technology contributes to its wide applicability. FDM (Fused Deposition Method) is the most known and popular 3D printing method due to its availability and affordability. It is also usable in design of technical objects – to verify design concepts with use of 3D printed prototypes. The prototypes are produced at lower cost and shorter time comparing to other manufacturing methods and might be used for a number of purposes depending on designed object's features they reflect. In the article, usability of 3D printing method FDM for designing of technical objects is verified based on sample functional prototypes. Methodology applied to develop these prototypes and their stand tests are covered. General conclusion is that 3D printed prototypes manufactured with FDM method proved to be useful for verifying new concepts within design processes carried out in KOMAG.

Key words: *3D printing, additive manufacturing, design, design process, FDM (Fused Deposition Method), prototype*

INTRODUCTION

Development and analysing of design concepts is integral activity within engineering design. Among methods that enable to verify a design concept is fabrication and test of prototypes. A prototype is a pre-production representation of some aspect of a design concept. It approximates a feature (or a number of features) of a product, service, or system.

In case of machine parts, fabrication of a prototype might be time-consuming and very expensive, depending on the properties that have to be included in the prototype. This applies in particular to situation when the prototype is to be tested on stand tests. The time and cost factors limit possibilities of verification of design concepts.

The problem indicated above regards situation when traditional manufacturing methods are used, like e.g. machining (subtractive methods), moulding. There is also a wide spectrum of additive manufacturing methods, commonly referred to as '3D printing', that enable to fabricate the final assembly parts. Depending on the properties of these parts and materials used, the manufacturing process still can be quite expensive, but at the same time much cheaper and faster than the traditional manufacturing process that would be applied otherwise. In particular also machine parts functional prototypes for verification of design concepts can be produces.

General model showing integration of 3D printing in product development process is presented in the Fig. 1.

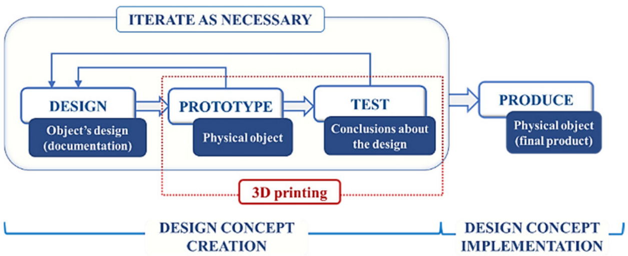

Fig. 1 Technical object development – general model

Among 3D printing methods there is FDM (Fused Deposition Method) that enables to fabricate, in a fast and cheap way, a physical model of a machine part that reflects its shape. Therefore, for machine parts functional prototypes reflecting their geometrical features can be produced.

KOMAG for years specializes in development of machines, devices and systems for mining industry. In many cases these solutions are also applicable for other industries. Among these solutions are nozzles for spraying systems and machine parts like magnetic clutches [6, 13, 17]. Both nozzles and clutches are components, manufacturing of which with use of traditional methods is time and cost consuming. Manufacturing of one or several prototype items is related with significantly higher investment cost compared to serial production. This affects possibilities to use their functional prototypes for design verification. In case of nozzles, their performance in strongly affected by their internal shape, and in case of magnetic clutches, their performance is strongly affected by arrangement of magnets. Therefore, these features are among subjects of conceptualization, and they both are strictly related with geometrical features of the components. The question that arose was, whether it is possible to verify new design concepts of nozzles and clutches via stand tests of their functional prototypes fabricated on an FDM 3D printer. Research carried out to find the answer is presented in this article. In particular methodology followed to manufacture 3D printed prototypes of technical objects and methodology followed to verify their usability for design concepts evaluation are described.

LITERATURE REVIEW

3D printing embraces a wide spectrum of very diverse manufacturing methods [12, 18], common feature of which is building an object by adding material in a layer by layer mode. Materials used, the way in which subsequent layers are built, 3D printers applied, and features of the objects produced depend on the 3D printing method.

3D printing has proved its advantages – compared to traditional manufacturing methods – in a number of branches and applications [3, 4, 7, 9, 11, 14, 15, 20]. In case of design process, these advantages are related with: possibilities to produce and test object prototypes as well as time and money spent for that purpose, overcoming limitations in design concepts and customization. FDM is the most popular and affordable 3D printing method, which is caused among others by high availability and affordability of desktop FDM 3D printers and materials – filaments.

Required properties of a prototype depend on the purpose for which it will be used. Properties of objects manufactured in FDM result among other from: filament used, object shape, object orientation and parameters (e.g. layers thickness, infill percentage, infill pattern) established for the 3D printing process [1]. There is a huge number of combinations of these elements affecting a 3D printout, e.g. its strength, surface roughness, dimensional accuracy. The relations between settings applied for 3D printing process and the final object obtained are a subject of research, results of which are presented in a number of publications (e.g. [5, 8, 10, 11, 16, 19, 21]). At the same time, there are no ready-to-use procedures to be applied to achieve required properties of a 3D printed protype, but the research results presented in articles can be transferred to other research as guidelines to follow.

DEVELOPMENT OF 3D PRINTED FUNCTIONAL PROTOTYPES – METHODOLOGY

Development of functional prototype of the new nozzle

Based on the literature research, material and object orientation were taken into account as these that will affect the 3D printed nozzle's strength, surface smoothness and accuracy in reflecting its 3D model's shape. To establish proper settings for the 3D printing of the new nozzle's functional prototype, first 3D printed model of already marketed nozzle was manufactured and tested. ZORTRAX M200 printer was used.

On the basis of the printer manufacturer's catalogue cards – five types of filaments were determined as applicable for 3D printing of the prototype nozzle. Z-ULTRA is one of them.

To decide on the nozzle's orientation, two items of a sample nozzle were 3D printed from Z-ULTRA material: one oriented vertically and one – horizontally. The STK-ZZ-2 nozzle, designed by KOMAG, was chosen for that purpose (Fig. 2).

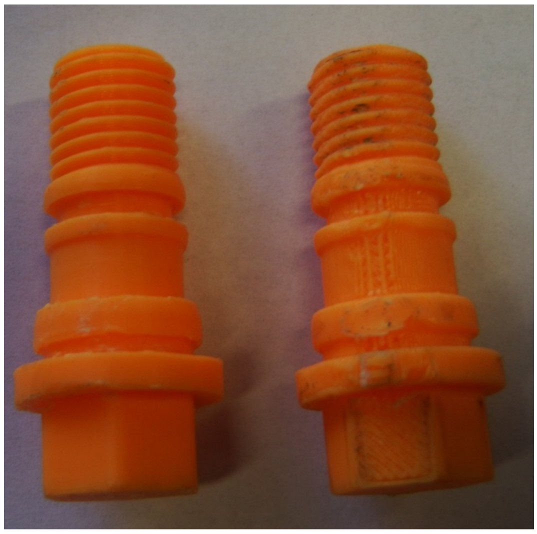

Fig. 2 Nozzle 3D printed: vertically (left), horizontally (right)

Vertical orientation brought definitely better results. The cylindrical surfaces of the nozzle remained smooth and maintained the circle shape of a cross-section. A much clearer thread outline can also be observed. In the nozzle printed horizontally, the cylindrical side surfaces are uneven and elliptical in cross-section. The indicated nozzle features are of great importance due to the correct embedment of the sealing O-ring and embedment of the complete nozzle in the matching hole of the feeding body. These conclusions regard surface features of a nozzle, not the internal ones that particularly affect the generated stream.

Next, it was established whether all filaments selected before as applicable for manufacturing the prototype nozzles indeed can be used for that purpose. In addition to the nozzles made of Z-ULTRA, items of STK-ZZ-2 were vertically manufactured from the following materials: Z-HIPS, Z-ABS, Z-PETG, Z-TRANSPARENT. Based on organoleptic assessment, each material was accepted for the tests to determine which of these materials is best for manufacturing the prototype of the new designed nozzle, taking into account the quality of the generated stream parameters (fractional distribution and range of the drops).

STK-ZZ-2 nozzles, namely 6 items made on the 3D printer and 1 item made of metal – purchased and used for comparative purposes (Fig. 3), were tested.

Fig. 3 STK-ZZ-2 nozzles: 1-5 printed vertically from Z-ULTRA, Z-HIPS, Z-ABS, Z-PETG, Z-TRANSPARENT, 6 - commercial, made of metal, 7 - printed horizontally from Z-ULTRA

The printed nozzles, cleaned out of residual material, were equipped with a set of O-ring seals. The air inlet and outlet of the nozzle were drilled to a nominal size of Φ2 mm, while the water inlet was corrected to Φ1 mm. In addition, the external thread was corrected with an M12x1.5 die. This was necessary due to the difficulties when screwing into the feeding body.

The following quantities were measured and recorded during the stand tests:

- particle diameter distribution in the spraying stream,
- supply pressure and volumetric air flow rate in the air mains feeding the nozzle,
- supply pressure and volumetric water flow rate in the water mains feeding the nozzle.

Photographic footage was also made to obtain information about the shape of the spraying stream.

During testing of the nozzle operational parameters (Fig. 4), their operation was tested at the same feeding pressure of water and compressed air in the range 0.3, 0.4, 0.5 and 0.6 MPa. The size of drops Dv(10), Dv(50) and Dv(90) was covered.

The last step is comparison of tests results obtained for the 3D printed nozzles with the results obtained for the one bought on the market. The Dv(50) indicator showing the maximum drop diameter of the half of sprayed liquid was assumed to be the most representative and most frequently used in the assessment of the quality of the spray stream.

Fig. 4 Test stand for testing quality of the spray stream
Source: [2].

Development of functional prototypes of the new clutches

KOMAG developed two designs of clutches (Fig. 5), in which the resistance force, which allows the transmission of torque, is generated by magnetic pairs.

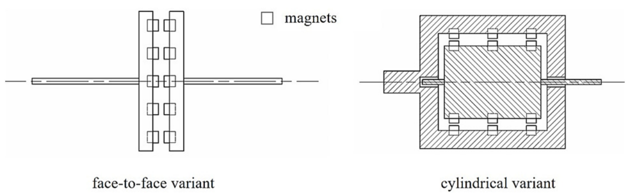

Fig. 5 Design concepts of magnetic clutches
Source: [6].

There were 3 prototypes in total: 1 for face-to-face variant, and 2 for the cylindrical variant. To produce prototypes of the new designed clutches, 3D printed elements and commercially available elements were assembled.

3D printed functional prototypes of these new solutions were manufactured for analysis of impact of magnets number and their mutual configuration on clutch parameters. The prototypes were manufactured in scale. The assumption was that the results obtained will then be used for development of full scale functional prototypes of the clutches being under design.

The designers had no possibility to establish the 3D printing parameters and make other adjustments based on prior 3D printing of the existing, already marketed solutions. Therefore, tailoring of the 3D model for 3D printing purposes as well as selection of settings for the 3D printing process had to be carried out – in an iterative way – during the 'fabrication and tests' cycles.

Due to shrinkage of the material during cooling down, for each prototype, several test prints were carried out to select the appropriate model deviations and obtain the required fits (magnets in the pockets, diameters for bearings, etc.) – Fig. 6a. Then the clutch components were printed and assembled together with the magnets and other elements (Fig. 6b).

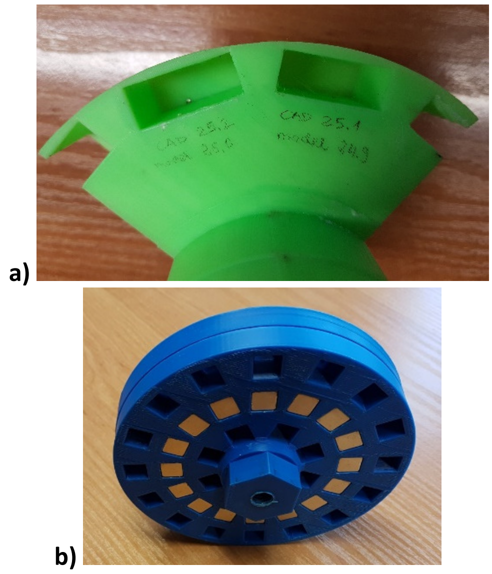

Fig. 6 a) a sample print of the clutch part, b) a physical model obtained after assembling the components

RESUTLS AND DISCUSSION

Tests of psychical models of the STK-ZZ-2 nozzle

Fig. 7 shows a change in the quality parameter of the Dv(50) stream depending on the feeding media pressure, for each STK-ZZ-2 nozzle, i.e. the steel one and the 3D printed ones.

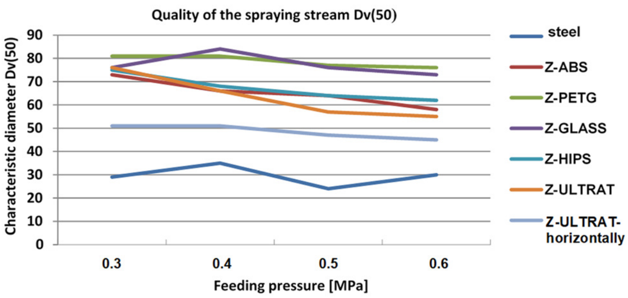

Fig. 7 Diameter Dv (50) for various STK-ZZ-2 nozzle materials

A nozzle made of metal in a subtractive manufacturing technology had the best atomization of drops in the spraying stream. A nozzle made of Z-ULTRAT material, printed horizontally, had similar parameters. Other nozzles, printed in horizontal orientation, showed slightly worse parameters. However, the correctness of improving the quality of the stream along with an increase in feeding pressure was maintained. The worse quality results of the spray stream of nozzles printed in the vertical orientation was most likely caused by the fact that the material layers in the nozzle were arranged perpendicularly to the direction of the stream outlet, which could disturb the process of breaking the water film.

To determine the possibility of longer use of spraying nozzles, they were subjected to a 15-hour work cycle. In the nozzle made of Z-PETG, the connecting thread damaged during the test, so no useful results were obtained. Comparison of parameters of the printed nozzles before and after the 15-hour cycle is shown in Table 1.

Table 1
Spraying stream parameters before and after a 15-hour cycle – comparison

Material of the nozzle	**Parameters of spraying water stream at feeding pressure 6 bar**									
	Water flowrate [dm³/min]		**Air flowrate [Nm³/min]**		**Diameter Dv(10) [µm]**		**Diameter Dv(50) [µm]**		**Diameter Dv(90) [µm]**	
	before 15 h	after 15 h	before 15 h	after 15 h	before 15 h	after 15 h	before 15 h	after 15 h	before 15 h	after 15 h
Z-ABS	0.37	0.35	0.097	0.096	18	17	**58**	**41**	125	90
Z-PETG	0.63	-	0.060	-	33	-	**76**	-	155	-
Z-HIPS	0.26	0.32	0.106	0.100	20	17	**62**	**56**	134	126
Z-GLASS	0.44	0.45	0.086	0.084	32	25	**73**	**61**	149	132
Z-ULTRAT vertical print	0.38	0.27	0.093	0.107	18	13	**56**	**38**	126	92
Z-ULTRAT horizontal print	0.38	0.27	0.096	0.107	18	19	**45**	**48**	92	97

The tests and measurements of spraying parameters of the tested nozzles proved that Z-ULTRAT material is best for printing the prototypes of nozzles, in a vertical orientation. STK-ZZ-2 nozzle printed from this material had the best parameters of spraying stream, and proved to be most durable during the fatigue tests. Therefor Z-ULTRAT materials and vertical orientation were applied for 3D printing of the functional prototype of the new designed nozzle.

Fabrication and tests of functional prototypes of the new nozzle

Poor mechanical strength is the main disadvantage of 3D printed nozzles. They are susceptible to damage when screwed into the feeding body. That is why an air-water nozzle plugged into a socket and secured with a STECKO-6 pin was designed. There were 3 variants (internal shape was the difference) of the nozzle. Both nozzles and the feeding body were 3D printed. Fig. 8 shows the nozzle prototypes and the feeding body equipped with G¼"clutchs and STECKO-6 pin. Places for the metal components (thread for connectors, pin holes) had to be included in the 3D model of the body. It was important to maintain proper manufacture tolerance, foreseeing the material shrinkage, so that the nozzles plugged into the body could be tightly fitted.

Fig. 8 Plug-in nozzle - 3 variants + complete feeding body

The spray stream generated by the plug-in nozzles was tested on the testing stand (Fig. 9). The operational parameters and the operational quality of the three nozzle variants are summarized in the Table 2.

Fig. 9 Test of the spraying stream of the plug-in nozzle

The new designed nozzle and its connection socket were significantly simplified, while maintaining the functionality and parameters of the spraying stream. The tests revealed that the plug-in nozzle (all 3 variants) is a very good replacement for the STK-ZZ-2 nozzle. All 3 nozzle designs produced the correct spray pattern.

The lowest water consumption was found in the nozzle with a cylindrical outlet and a water inlet tangent to the chamber. This nozzle also had the best quality of the spray stream atomization. Fig. 10 shows a change in the basic quality parameter of the Dv(50) stream depending on the feeding media pressure for each nozzle variant. As the pressure of the spraying media increased, the quality of the spray stream generated for each nozzle slightly increased.

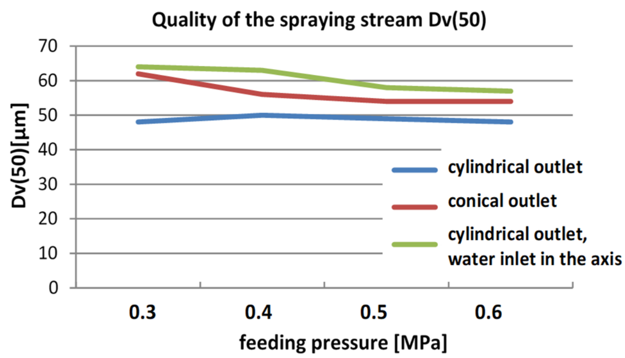

Fig. 10 Characteristic Dv(50) diameter for different plug-in nozzle variants

Table 2
Plug-in nozzle measurement results

Feeding media pressure [water/air] [MPa/MPa]	Operational parameters of water stream from plug-in nozzles: D1 – cylindrical outlet, D2 – conical outlet, D3 - cylindrical outlet, water opening in the axis														
	Water flowrate [dm³/min]			Air flowrate [Nm³/min]			Diameter Dv(10) [μm]			Diameter Dv(50) [μm]			Diameter Dv(90) [μm]		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
0.3/0.3	0.16	0.19	0.25	0.041	0.064	0.052	18	25	29	**48**	**62**	**64**	106	132	124
0.4/0.4	0.19	0.29	0.32	0.060	0.079	0.071	18	23	29	**50**	**56**	**63**	108	117	118
0.5/0.5	0.26	0.55	0.50	0.071	0.085	0.075	19	23	27	**49**	**54**	**58**	103	116	110
0.6/0.6	0.34	0.66	0.52	0.095	0.095	0.093	20	23	25	**48**	**54**	**57**	96	118	104

The tests confirmed that use of FDM for manufacturing of prototypes of nozzles is usable for testing of their new designs, and brings reliable results.

Fabrication and tests of functional prototypes of the new clutches

Face-to-face clutch consists of two discs with magnet pockets that interact with each other to transmit torque. They were designed so that the diameter of the magnet arrangement could be changed (Fig. 11). The change in the magnet arrangement diameter is possible by using the sockets of diameters Φ46.5, Φ79.1 and Φ111.7 mm.

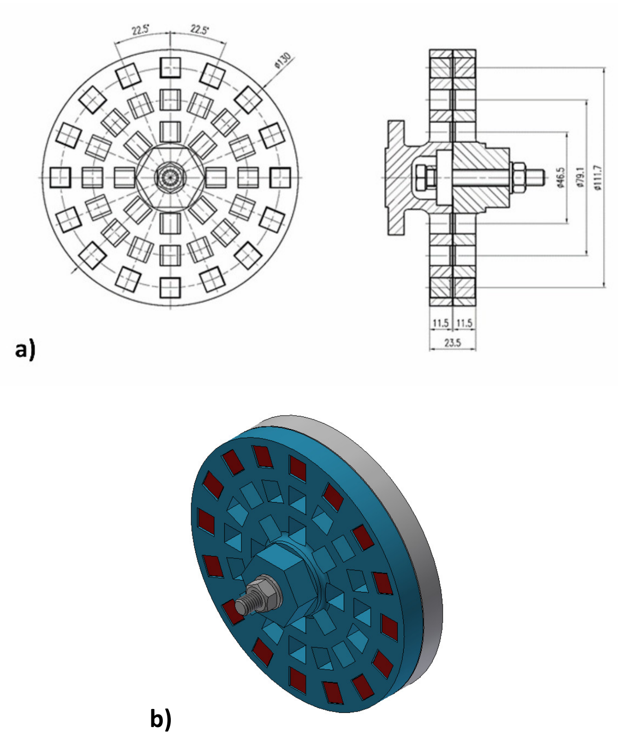

Fig. 11 Face-to-face clutch:
a) sketch, b) 3D model
Source: [6].

The coaxial clutch was designed in two variants – single-row and double-row. For each of them a physical model (fictional prototype) consisting of the following components was created:

– printed components: rotor, stator and cover; the cover is identical in both variants, the other components have an individual design
– bearings, fixing screws and MPŁ 10x10x10 N42 type magnets.

The sketch, spatial model and printed components of the single row cylindrical clutch are presented in Fig. 12, Fig. 13.

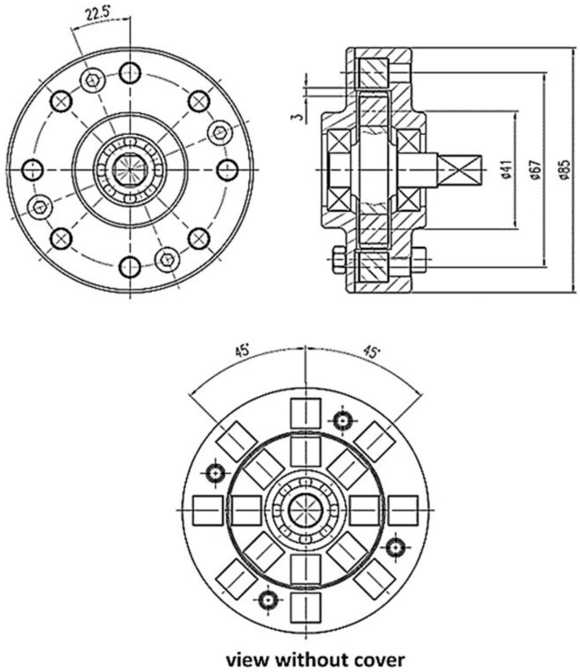

Fig. 12 Single row cylindrical clutch – sketch
Source: [6].

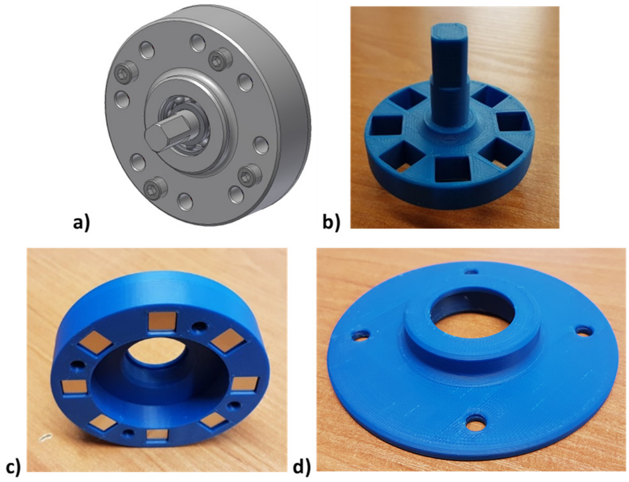

Fig. 13 Single-row cylindrical clutch:
a) 3D model, b) rotor – print, c) stator – print, d) cover – print
Source: [6].

The assembled physical model of the clutch is shown in Fig. 14.

Fig. 14 Physical model of a single-row cylindrical clutch
Source: [6].

The physical model was subjected to static tests to determine the limits of the transmitted torque. During the tests, the structure of the clutch shaft was damaged due to exceeding of the structure strength in a result of applied loads (Fig. 15).

Fig. 15 Damaged rotor shaft of the single-row cylindrical clutch
Source: [6].

Insufficient rotor shaft strength resulted from the fact that the filling level was too low when the core was printed. Another rotor print was made, in which the maximum filling of the print core possible to obtain on the printer was used. This allowed for the successful completion of subsequent tests.
The basic dimensions of the double-row cylindrical clutch and the 3D model are shown in Fig. 16. Printed components of the clutch are shown in Fig. 17. Fixing eyes were added to the stator for subsequent stand tests.

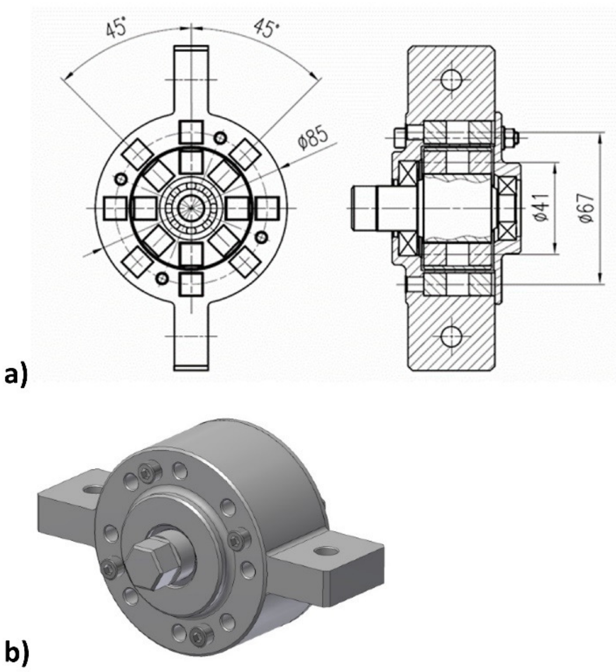

Fig. 16 Double-row cylindrical clutch:
a) sketch, b) 3D model
Source: [6].

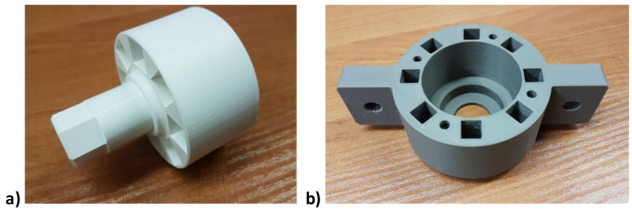

Fig. 17 Printed parts of a double-row cylindrical clutch:
a) rotor, b) stator
Source: [6].

To avoid the problem of insufficient rotor strength in a single-row clutch, the rotor was printed from a material with higher strength and the degree of filling of the model was increased. The material used to print the stator remained unchanged. Due to the expected higher resistance torque of the double-row clutch variant, the connecting part was made as a hexagon (wrench 17).
The physical model of the clutch that was tested is shown in Fig. 18.

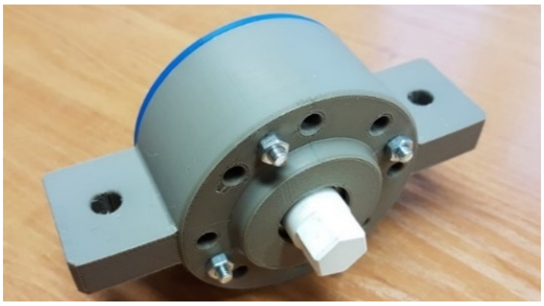

Fig. 18. Physical model of a double-row cylindrical clutch
Source: [6].

After the clutch models were made, preliminary tests were carried out to determine the rolling resistance generated by each variant of the clutch. Sample results are presented in Fig. 19. Details regarding the tests and the obtained results are presented in [6].

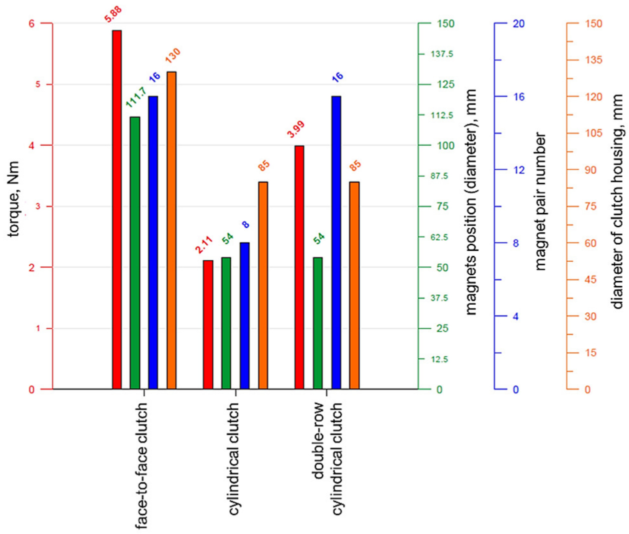

Fig. 19 Rolling resistance of each clutch in relation to their design features

Prototypes of clutches created with use of the parts manufactured by 3D technology proved to be sufficient for testing and obtaining useful results on the basis of which the selected aspects of the proposed designs could be verified.

It should be emphasized that with FDM method it is possible to create (and test) prototypes for a number of design variants with relatively low investment costs and required time, which increases the probability of obtaining the optimum solution.

CONCLUSIONS

Application of FDM in design process can be done in particular to verify a design concept of technical object via stand tests of its prototype carried out e.g. to establish important working parameters or other properties.

Capabilities and limitations of the 3D printer used, material, and 3D printout orientation are examples of factors that affect surface and internal properties of 3D printed prototype, and – consequently – affect reliability of the prototype tests results. If the designed component is a modification of already existing ones, it is worth to make a decision concerning the above mentioned factors on the basis of the stand tests carried out for an object of known, already implemented design – tests of the object (items bought on the market) and tests of its 3D printed model. This was done in the case of printing and testing of prototypes of new nozzle design solutions. Comparison of the test results of a nozzle available on the market and its 3D printed models allowed to select materials and object orientation for 3D printing of prototypes of new designed nozzle. In the case of 3D printed prototypes of clutches, it was not possible to carry out stand tests for existing structures (clutches) that would provide useful information. On the other hand, in the case of coaxial clutches, experience from previous tests of the single-row variant allowed to take decision about change of parameters (filling density) for 3D printing of the next item of rotor, as well as for 3D printing of the first item of rotor for the clutch model in the double-row variant.

When designing machine parts, systems, etc., commercial parts are used alongside absolutely new designed parts. The use of the FDM method allows to create prototypes by combining printed and commercial components, and use them for tests to verify parameters for which such prototypes are sufficient (allow to obtain reliable information). The discussed physical models of clutches are an example.

If a prototype is assembled from 3D printed parts and ready-to-use components (not being subject of the design process), it is important to make test prints – limited to a fragment of the component – to select the deviations in the 3D model and guarantee a proper fit of the prototype's components. This approach saves time, enables to avoid wasting of material, and was used when manufacturing clutch prototypes.

The examples discussed in this article support the following statements regarding 3D printing:

– it gives wide possibilities and easiness in development of new design concepts
– it gives hight easiness and flexibility in manufacturing of prototypes
– it gives possibilities to adjust prototypes for testing purposes
– all abovementioned advantages are achieved at low cost and short time comparing to traditional manufacturing methods.

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