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Geometrical Accuracy of Flexspline Prototypes Made by FDM/MEM Methods

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Abstract. This article presents an analysis of the geometrical accuracy of flexspline prototypes that were a component of harmonic drive. To produce the test models, a MEM (Melting and Extrusion Modeling) method was used. This additive method allows the production of elements with very complicated shapes from various polymeric materials. As the test model, a flexspline made of ABS (acrylonitrile-butadiene-styrene) was assumed. Such a special gear with a complicated construction was chosen, because its unique design allows one to obtain clear conclusions from the analysis. To expand the scope of research, models of flexspline with four different construction solutions were made and tested. As a step of the analysis, contact measurements were performed for several flexspline models on the coordinate measuring machine to check their dimensions. The verification of the geometrical accuracy of flexspline models will allow to assess the usefulness of additive methods for the production of prototypes and finished products.

Introduction

Rapid prototyping (RP) methods are a group of technologies currently universally used in many sectors of industry [1,2]. Their advantages are not only used in prototyping processes, but are often the main manufacturing method of machine parts. The quality of products manufactured by additive methods depends mainly on the method itself, but also on the materials used in the production process [3-5] and imposing its quality [6,7]. For most manufactured elements, dimensional accuracy is very important. It allows to ensure the basic functions of the product and ensure proper cooperation with other machine components. The diversity of additive methods used for the production of machine components does not allow for their overall assessment. Therefore, for each of them, it should be conducting tests on prototypes in the initial phase of product design regarding their dimensional accuracy and functionality [8,9]. For machine components operating with load, strength and durability analyses should also be carried out.

Rapid prototyping is a technique that supports both the design and implementation processes of new solutions. This significantly saves energy [10-12] and reduces environmental impact [13]. However, depending on the rapid prototyping technology used, it often involves unsatisfactory accuracy and quality [14], which often requires finishing processing. Such an approach often requires organizational changes [15], the development of new failure mode and effects analysis scenarios [16-18], and the implementation of precise measurement and control techniques [19]. Rapid prototyping has a wide range of applications and often involves the application of special coatings [20,21], including DLC [22-24] or electrospark deposition [25,26], modification of the morphology of the surface layer [27], or welding joints [28]. The presented article introduces a prototype of a flexible cup for a harmonic drive, which due to its significant possible gear ratios and high precision, can find applications in hydraulic control [29-31] and the military sector [32-34]. Due to the multidimensional dependencies, the implementation of formal statistical techniques [35-37], including expert systems support [38] and nonparametric approaches [39-41], is necessary.

Materials and Methods

In the research, the flexspline of the harmonic drive was included. It is a gear with a thin-walled body with a flat bottom at one end and a toothed wheel rim on the other side of it (Fig.1). The unique sleeve design causes very big problems when making a flexspline by classic reductive machining. In addition, during work, it is deformed by a generator, causing its precisely defined deformation [42]. The small-module toothed wheel rim of the flexspline meshes with the circular spline, transferring the torque to the other gear components. Harmonic drives are characterized by very high kinematic accuracy, so to provide it, the geometrical accuracy of the flexspline itself is also necessary. Unfortunately, a big problem is the relatively low durability of these gears, thus new constructions are constantly being designed. The new shapes of flexspline will reduce stress levels in their body, and so increase the strength and durability of harmonic drives. The use additive methods for the production of such special gears offers new technological potentials. Layered adding of next cross sections of the flexsplines allows them to be made in new shapes that were previously impossible. Additive manufacturing does not require any additional tooling or special tools, and many maintenance operations are automatic.

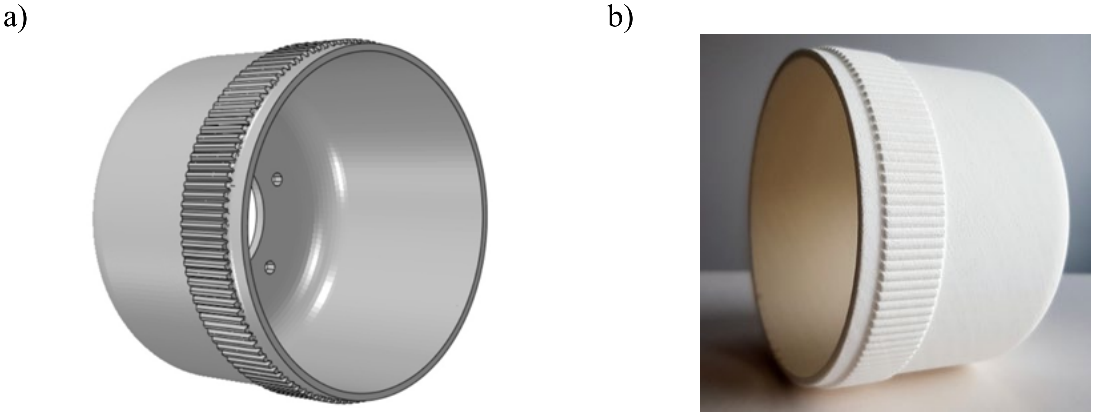


Fig. 1. Standard flexspline of harmonic drive: a) numerical CAD model, b) prototype made by additive method

Prototyping

The MEM method was used to make physical models of the flexspline of harmonic drive. It is a variation of the FDM (Fused Deposition Modeling) method adapted to devices from company TierTime. This method was chosen due to its high availability among additive manufacturing technology and its growing popularity, which guarantees its rapid development [43,44]. The relatively low price of devices used in the FDM method, with many of its advantages, makes it applicable not only for the manufacturing of prototypes but also in the production of finished products. UP Plus 2 and UP mini 2 printers with a single nozzle numerically controlled head were used to produce test models of flexspline.

Because they are printers from the same producer, they have the same dedicated software to prepare models and printing. The UP Studio program (Fig.2a) was therefore used to import models of flexspline as the STL file, prepare the printout and control it. The process of printing a flexspline on the UP mini 2 is shown in Fig.2b.

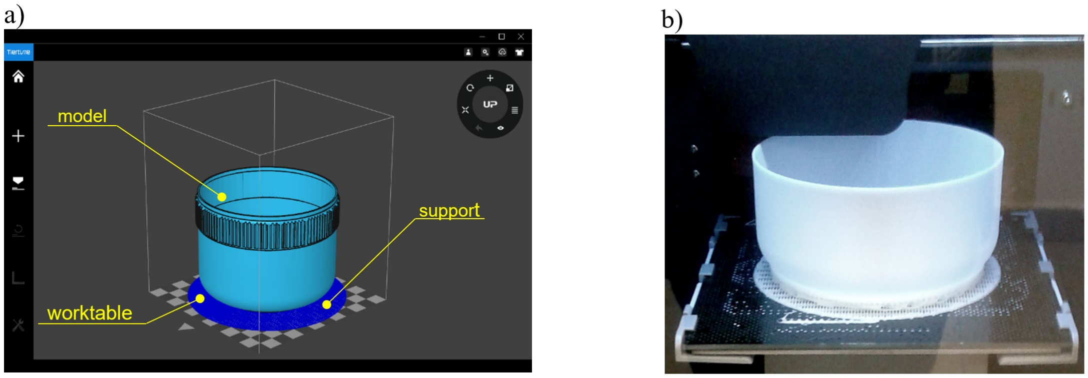


Fig. 2. *Preparation of printing models: a) the UP Studio program with a flexspline model, b) a flexspline model of flexspline, b) model of the flexspline during printing*

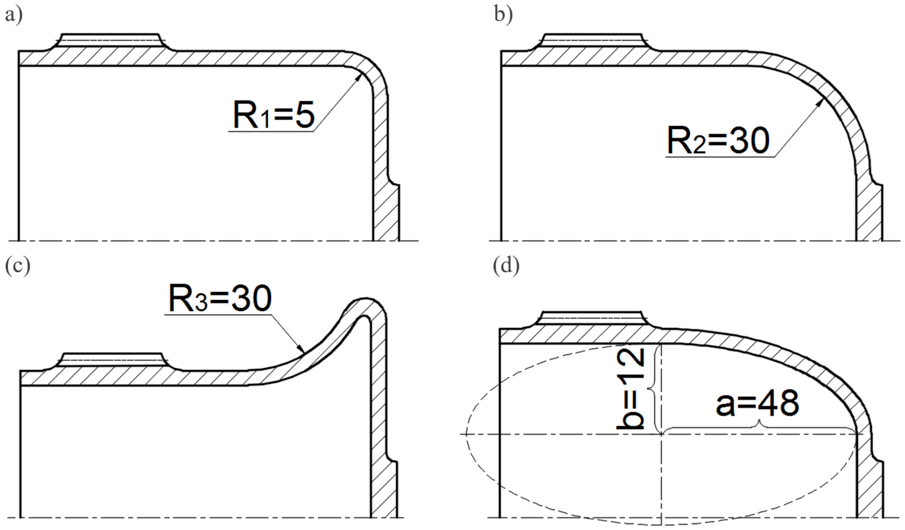


Fig. 3. *Design variants of flexspline models in variants: a) base, b) with enlarged radius, c) with external flange, d) elliptical*

For bench research, several models of flexspline were made, which differed in the shape of the body sleeve. Four variants of construction were selected, together with characteristic geometric parameters, which are presented in Fig.3 with simplified. All wheels were designed based on the same geometric assumptions, and only the dimensions indicated in figure 3were changed. For every of the design variants, models were made while maintaining the same settings of 3D printers and from the same material, which was ABS [45].

Analysis of Prototypes Geometry

After each of the physical models was made, they had to be checked for completeness and correctness of shape. In addition to the general assessment of the condition of the model, the supports had to also be removed and cleaned.

For the prepared physical models of the flexspline, an evaluation of their selected geometrical parameters was performed. Precise control of models produced using the MEM method included two stages:

- initial verification of the main dimensions of the flexspline model.
- checking the accuracy of the surface mapping of the physical model in relation to the CAD output model.

The comparison of the results of the measurements obtained in each step did not show any general differences. However, local divergencies appeared in few cases, resulting from errors characteristic of the applied incremental method. There were sometimes point blobs or gaps of the material on the model, caused by the out-of-control over the melted material in the 3D printing process. A common problem in the manufacturing of models using the FDM/MEM method is the shrinkage of the material that is other than that assumed by the producer. Initial measurements concerned checking the dimensions of the printed models, the wall thickness of the flexspline sleeve, and the diameters of the holes using a caliper. Evaluation of the dimensional accuracy of the printed physical models provided satisfactory results. None of the products had significant differences between the theoretical and the real dimensions. The observed dimensional differences of less than 1% should be taken as a very good result considering the measuring tools used. This proves both the high accuracy of the 3D printers used, and the correct design of the manufacturing process, the proper selection of its parameters, and the use of good materials.

The analysis of geometrical parameters of physical models made by the rapid prototyping method cannot be limited only to general dimensional control. Therefore, the thin-walled models produced by the MEM method were measured precisely using the contact direct method. Measurements were performed using a Roland MDX-40A coordinate milling machine (Fig.4), additionally equipped with a ZSC-1 scanning head [46]. The contact scanning process was chosen due to the high accuracy of the method, and the need to measure models with both large dimensions and detailed toothed wheel rim area. The scan is performed by direct contact of the scanning head tip with the measured material, so it does not require any additional model preparation. Fig.4 shows the process of scanning the flexspline on a coordinate measuring machine. The enlarged fragment (Fig. 4b) shows the tip of the scanning module in relation to the measured teeth with a 0.7mm module.

The scanning process consisted of making measurements in the coordinate system of the CNC machine at the moment of contact of the head with the surface of the model. The scan result is saved in the form of a point cloud, and can also be converted into a triangle mesh, creating a numerical model of the measured part.

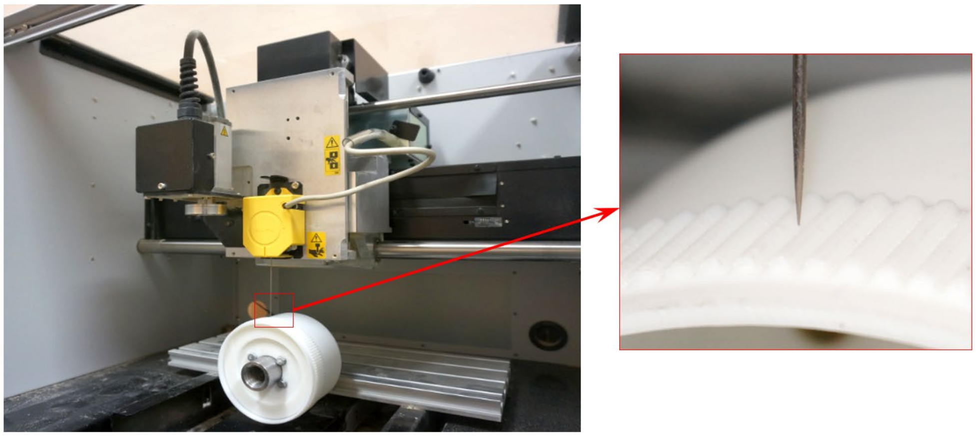
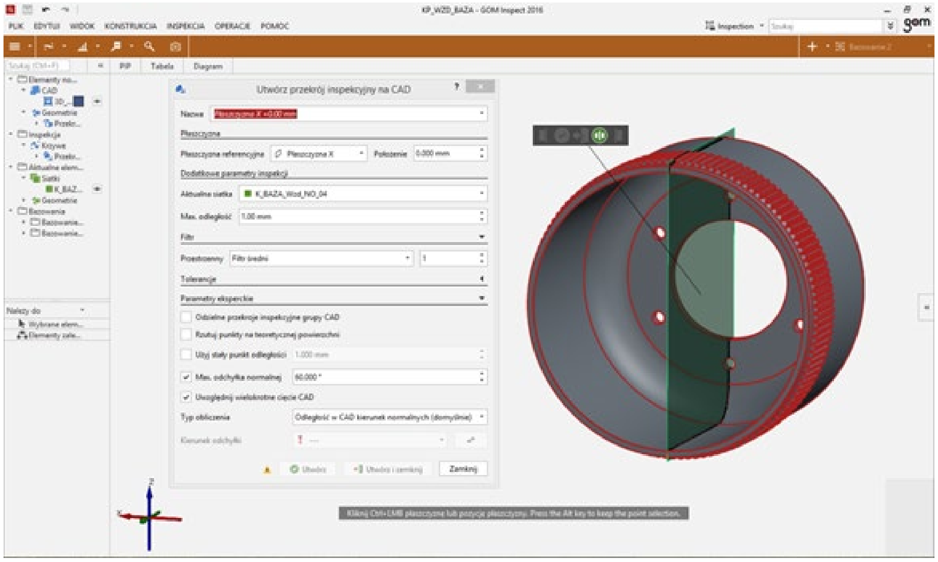


Fig. 4. *Measuring a flexspline model on a Roland MDX-40*

The analysis concerned precise linear measurements in maincross sections on models of flexspline. For all tested wheels, a measurement was performed in the plane along their axis, passing through the center of the tooth space. To perform the analysis of dimensions, multiple scans of each of the flexspline physical models were performed, comparing the obtained results. No clear differences were observed between the subsequent measurement results.

Based on the results of the gear measurements, a more accurate analysis of the accuracy of their execution was performed using the specialized GOM Inspect program. It is universally used as inspection software for final quality control on production lines. It allows to download and analyze data from various measuring machines, but also to analyze any surface in the form of a point cloud [47-49]. Measurement results concerning external profiles of flexsplines and also CAD models of flexsplines were imported into the GOM Inspect program. Since the CMM measurement was performed only in the main axis of the flexspline, a cross-section in program was defined on the same plane from the full 3D model. A control cross-section was therefore defined in order to compare the theoretical values with the results measured for the prototype of the flexspline. The GOM Inspect window, with the tool to create a cross section based on a CAD model, is shown in Fig.5.



Utwórz przekrój inspekcyjny na CAD

Nazwa: Płaszczyzna X +0.00 mm

Płaszczyzna

Płaszczyzna referencyjna: Płaszczyzna X Położenie: 0.000 mm

Dodatkowe parametry inspekcji

Aktualna siatka: K_BAZA_Wod_NO_04

Max. odległość: 1.00 mm

Filtr

Przestrzenny: Filtr średni 1

Tolerancje

Parametry eksperckie

☐ Oddzielne przekroje inspekcyjne grupy CAD

☐ Rzutuj punkty na teoretycznej powierzchni

☐ Użyj stały punkt odległości 1.000 mm

☑ Max. odchyłka normalnej 60.000 °

☑ Uwzględnij wielokrotne cięcie CAD

Typ obliczenia: Odległość w CAD kierunek normalnych (domyślnie)

Kierunek odchyłki: —

Kliknij Ctrl+LMB płaszczyznę lub pozycję płaszczyzny. Press the Alt key to keep the point selection.

Fig. 5. *View of the GOM Inspect window*
with the active command to define a section on the CAD model

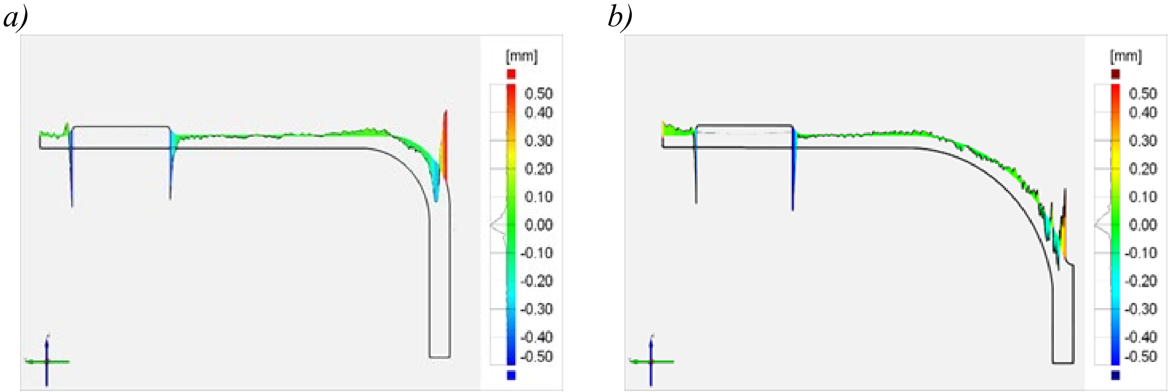


Fig.6. *Dimensional deviations for the flexspline:*
a) base variant, b) enlarged radius variant

a) *b)*

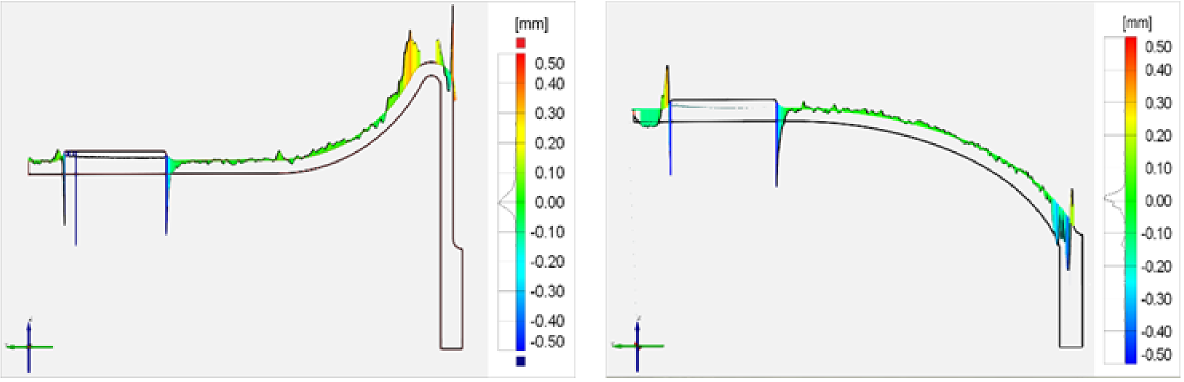


Fig.7. *Dimensional deviations for the flexspline:*
a) variant with outer flange, b) elliptical variant

The result of the control of the accuracy of the models is presented in the form of deviations between the real and theoretical outline. They can be read for individual points, or in a more representative graphic form as a graph on the created cross-section. Figures 6 and 7 show the deviation diagrams obtained in the GOM Inspect program for the longitudinal cross section of the flexspline of the harmonic drive. It can be seen that the divergencies between the real and theoretical models are not large. Innermost deviations do not exceed 0.05 mm, and these values exist mainly on the body of the flexspline.

The biggest differences are noticeable in the transition radius between the toothed wheel rim and the body sleeve and near the bottom. In these areas, the profile is not parallel to the axis of the wheel, so the layered structure of surfaces strongly affects the values of the measured dimensional deviations. Also, the processing shrinkage of the material, which resulted the shortening of the physical models, has an impact on the divergencies exactly in the width of the gear rim and the total length of the flexspline. Dimensional differences can be also a effect of errors on the external surface of the physical models at the bottom of the flexspline, due to the use of support structures during printing. After removing the supports, small shifts or discontinuities of the material layers often remain in the place of their attachment, which resulted in high values of deviations near the bottom, in the graph regarding the base variant.

The description attached to each of the charts contains a histogram showing the distribution of results for given deviation values. This provides the information that the majority of the profile obtained as a measurement of real models is compatible with the theoretical one, or very close to it. Therefore, the quality of physical models printed using the MEM method from ABS material can be highly evaluated. However, after their production, shrinkages occur and appropriate scaling of CAD models should be applied to avoid dimensional errors in functional prototypes.

Conclusions

The analysis of the dimensional accuracy of the models produced using the FDM/MEM method from ABS polymer confirmed the legitimacy of using 3D printing for the production of functional prototypes of harmonic drives. However, already at the design of the elements, the characteristic material parameters and limitations of additive methods should be implemented. The production of real models from polymer materials should assume the physical characteristics specific to each material. Especially for large models, material shrinkage can significantly affect the dimensions of products. In the case of the MEM method, in which the material is applied in layers, it is also important to position the model relative to the direction of printing. The element should be positioned in such a way that surfaces especially important for strength or appearance are in one layer. In the direction of applying the layers of the model, there are disturbances in the external surfaces, the size of which depends on the resolution of the 3D printer.

The verification showed a relatively high geometrical accuracy of the flexsplines models produced by additive methods. Of course, the dimensional accuracy and external structure of the prototypes provided cannot be compared with the quality of models made of polymer materials by injection molding. Steel models of the flexspline also have much higher dimensional accuracy, quality of external surfaces, and strength. However, only incremental methods allow one to obtain ready-made flexsplines without the use of extra handles, molds, or specialized tools, which greatly reduces production costs. Often, dimensional accuracy is not a main parameter determining the possibilities of using the product. This is the case with the analyzed harmonic drive, which has a unique principle of operation. In this type of gears, there are several or even tens of pairs of teeth that are meshing at the same time. Such a way of working together with the forced deformation of the flexspline causes the initial geometric to be not so important. In the case where the wave gear is not very much loaded, it can be made successfully of polymer materials by additive methods, which is cheaper than other technologies. However, it should be seen that the process of printing wave gear components is much lengthier than, for example, injection into molds. Therefore, additive methods can be used successfully for the production of prototypes and for small production for less demanding finished products. When designing machine elements for production with use one of the rapid prototyping techniques, they should be constructed in such a way as to take full advantage of the benefits, and avoid problems resulting from the limitations of the chosen method.

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