Materials Research Proceedings **5** (2018) 61-66 doi: http://dx.doi.org/10.21741/9781945291814-11

Analysis of Possibilities of Using Polymeric Materials for Testing Prototypes of Harmonic Drive

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Keywords: Harmonic Drive, Flexspline, Polymeric Materials, 3D Printing, FDM, MEM, Coordinate Measurements

Abstract. The main objective of the analysis was to assess the suitability of rapid prototyping methods to perform functional prototypes of a harmonic drive. Physical models of a gear wheel for the harmonic drive were made and geometric accuracy control was carried out therefor. Precise measurements of tooth profiles showed differences between models made with the use of 3D printing and corresponding theoretical outlines. The discrepancies were not decisive for the correctness of the work of the analyzed harmonic drive, since the key parameter affecting its kinematic accuracy is the scale's constancy.

Introduction

Harmonic drives are a special type of gear transmission, mainly due to an extremely complex way of load transfer. Their basic components are flexsplines, in the shape of a thin-walled sleeve with an external toothed ring, a circular spline and a wave generator. The basic diagram of such a gear is shown in Figure 1a.

The rotating generator deforms the flexspline, causing its moving in relation to the circular spline with internal teeth. Toothed rims of both wheels meet in the meshing areas, and pass each other outside of these areas [1, 2]. The load is transferred simultaneously by 20 ÷ 50% of the total number of teeth of the flexspline [3, 4]. These exceptional working conditions bring on the need for a very thorough stress analysis [5, 6] to improve the quality of this type of gears. Analytical calculations of this type of gear are not accurate, because the complexity of the problem forces the basing only on general assumptions. Numerical calculations carried out, for example, using the FEM finite element method are based on simplified models, so they also do not give precise results. Only bench tests allow for the exact determination of the strength and durability of a gear, as well as the assessment of the quality of its work or kinematic accuracy.

Experiments are carried out with the use of functional prototypes, often by rapid prototyping (RP) methods, from polymer materials. The use of the 3D printing method allows for fast and cheap production of all components of the gear. This is particularly important in the case of a flexspline of a harmonic drive, whose thin-walled construction causes a lot of technological problems during production with classical cutting methods. Therefore, the use of additive methods of rapid prototyping not only facilitates the creation of flexsplines, but opens up new opportunities to improve their design. The key issue, however, is the geometric accuracy of harmonic drives made by 3D printing.

Model making

The implementation of a functional prototype of a harmonic drive must be preceded by analytical calculations in order to determine its basic geometrical and strength parameters and to model its

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components in the selected CAD program. For the needs of gear production for harmonic drive, the MEM (Melting and Extrusion Modeling) method was chosen, i.e. FDM (Fused Deposition Modeling) with a single nozzle print head [7, 8]. It is an incremental shaping technology that allows for creating physical models with complex geometry, which is especially important in the case of a flexspline of a harmonic drive. The obtained surface quality is not comparable with other methods [9, 10], especially in mass production, but sufficient for prototyping. The ABS copolymer (acrylonitrile butadienestyrene) is one of the most often used materials in 3D printing, with strength and temperature parameters that allow it to be widely used both in industrial production and for prototyping [11, 12].

Measurements
A detailed analysis of geometric accuracy of models made with the use of 3D printing was performed using a Roland MDX-40A coordinate milling machine with a special ZSC-1 scanning head mounted (Fig.2b). The measurements were carried out using the contact method due to its high accuracy and the possibility of using models immediately after their manufacture.

a) b)

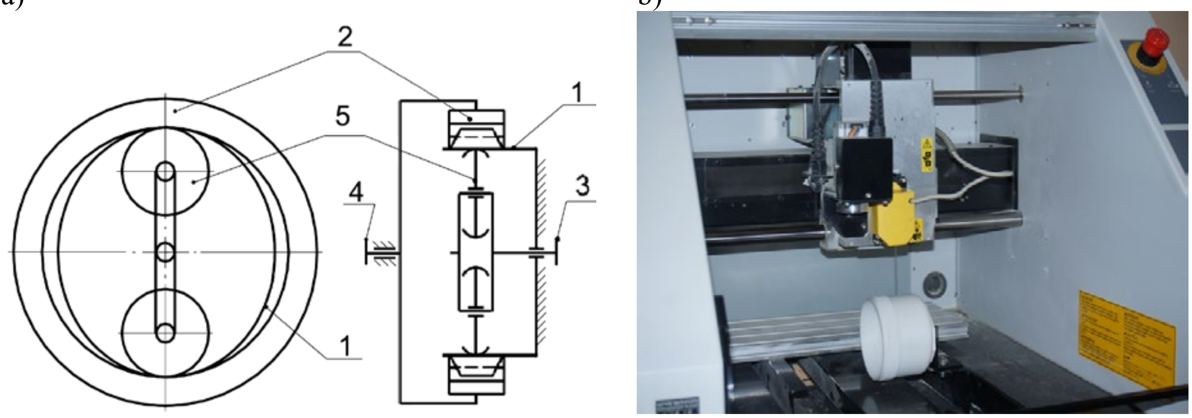

Fig. 1. Harmonic drive: a) scheme: 1-flexspline, 2-circular spline, 3-input shaft, 4-output shaft, 5-two-roll generator, b) measurement of the profile of the flexspline in a longitudinal section on the Roland MDX-40 cnc milling machine.

The gear wheels mounted in the tested harmonic drive have teeth which are about 1mm high. Therefore, a very small diameter of the scanning module measuring tip of 0.04mm is an additional factor determining the choice of this coordinate machine. The process of spatial models scanning consists in making measurements in the X, Y, Z coordinate system of the CNC machine when the head contacts the surface of the model. The scan result is obtained in the form of a points cloud, or after processing as a triangle grid. In this form it is saved for further processing and analysis.

Longitudinal section of the flexspline
Firstly, the outer surface of the flexspline was scanned in its longitudinal section passing through the middle of the inter-tooth groove. The view of the obtained profile along with the enlargement of characteristic areas is presented in Figure 3.

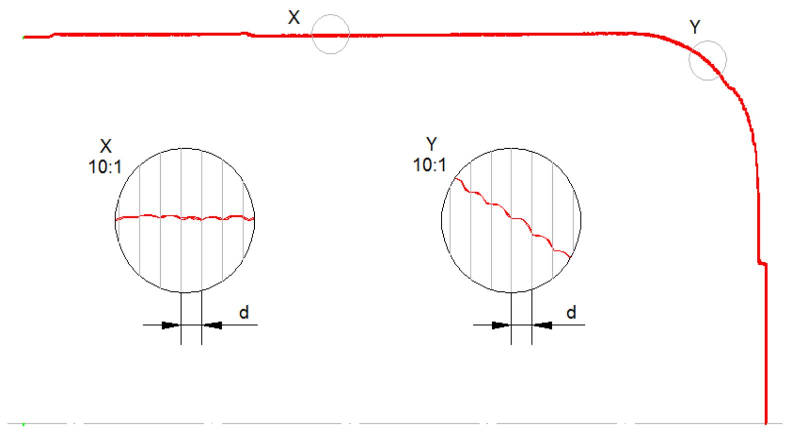

Fig. 3. The result of scanning of external profile of the flexspline.

The measured overall length of the flexspline equaled 69.87 mm and was slightly smaller than the nominal size of 70mm. However, it was about 0.48mm smaller from the value obtained during the initial measurements, made immediately after the model was printed. This reduction of overall dimensions is mainly a result of a processing shrinkage which in the case of ABS is up to 0.7%, i.e. for the analyzed model equals about 0.5 mm. Because the scanning of the gear wheel models was carried out long enough from their production, the reduction in length is a correct behavior resulting from the properties of the used material.

Figure 3 also shows the enlargement of the X and Y areas, related to the external outline of the flexspline of the harmonic drive obtained in the process of scanning. In the X area, the external surface of the model is cylindrical, and the outline obtained as a result of scanning is close to the linear one. Measured deviations from the average value do not exceed ± 0.25 mm, which should be considered as a very good result for the incremental method of model producing. However, when the external outline of the model ceases to be parallel to the direction of layer application, the quality of the external surface is getting worse. This is clearly visible on the Y magnification, where the profile of the flexspline body obtained in the measurements has a clearly stepped course. Individual layers can be recognized thereon and they are marked with lines to improve readability. The distances between successive lines equalled 0.1mm, which is exactly the same as the thickness of a single layer for 3D printing. In the case of the prototype of a flexspline, this has a negative effect only on the appearance of the external surface of a model, and does not affect its strength.

Teeth profiles in a cross-section

Checking the geometric accuracy of gear wheels should particularly concern areas that have a direct impact on their correct working. In the case of harmonic drives, it is very important to properly shape the small-module gear rim. When making 3D printing wheels with small teeth, the diameter of a nozzle that provides the molten material is a very important parameter. The minimum radius of rounding of all external corners on models depends thereon. In the case of gear wheels for harmonic drives, a problem may arise in the precise reproduction of a theoretical outline of teeth. Therefore, the models produced by the FDM / MEM incremental shaping method have been subjected to precise measurements also in this field. The shape of a tooth obtained on a physical model is significantly different from a theoretical one. To notice the differences, not only in relation to the correct outline, but even between successive teeth, it is enough to visually assess the profiles in a few-size magnification. The lack of sharp corners on models made with the FDM / MEM method is a result of its technical limitations. The machine used for 3D printing had a nozzle with a diameter of 0.4 mm.

With such limitations, it is not possible to obtain external corners with a radius smaller than the dimension of the hole in the nozzle supplying the material.

However, the assessment of the accuracy of gear wheels of harmonic drives is not based on the accuracy of the representation of the outline of individual teeth [13]. In these drives, wheel cooperation takes place due to a simultaneous meshing of even several pairs of teeth, which is why maintaining a constant scale is a more important criterion. It is also common to use outlines of teeth other than involute teeth in this type of gears, and their selection depends on production capacity [14]. There are also solutions with a rectilinear outline of the tooth's side, because at a small height and high correction factors used, the difference with regard to the used involute fragment is not significant. Experience suggests that flexspline defects occur most often in places where the thickness of a susceptible sleeve changes or in the grooves between teeth. Thus, the shape of a tooth does not have a significant impact on the strength of harmonic drives.

Averaged scan results for the grooves and tooth width as well as the scale of the teeth of both wheels are given in Table 1. They were compared with the reference values for the theoretical outline.

The results presented in Table 1 show a large convergence of measurement results with theoretical values. This is surprising, with respect to the previous preliminary assessment of the outlines of the teeth, whose profiles differed significantly.

Table 1. Selected tooth dimensions of the physical and theoretical model.

		Tooth's width [mm]	Groove's width [mm]	Scale [mm]
Susceptible wheel	Theoretical outline	1,552	1,055	2,607
	Scanning result	1,513	1,073	2,586
	Variation	***0,039***	***-0,018***	***0,021***
Rigid wheel	Theoretical outline	1,375	1,192	2,547
	Scanning result	1,369	1,214	2,583
	Variation	***0,006***	***-0,022***	***-0,016***

The discrepancies between the averaged tooth width values for the flexspline and circular spline are 0.039mm and 0.006mm, respectively. Also the widths of the grooves between the teeth, measured for both physical models, are very close to the theoretical values, and the differences are at the resolution level of the scanning method, so they can be ignored. Thus, the requirements regarding the most important geometrical parameters determining the kinematic accuracy of the harmonic drive have been met.

The analyzed harmonic drive is a special construction, where the teeth of the flexspline move along a complex trajectory on a shape which is influenced by simultaneous radial and peripheral displacements and the angle of twisting of the tooth axis. Therefore, when designing harmonic drive wheels, considerably greater interstices are expected in order to eliminate the phenomenon of interference. When the generator rotates by an angle of $0° \leq \varphi \leq 180°$, the tooth of the flexspline moves from one groove to the next. Figure 4 shows the subsequent positions of the flexspline's tooth which are a result of the generator rotation, for the theoretical outline.

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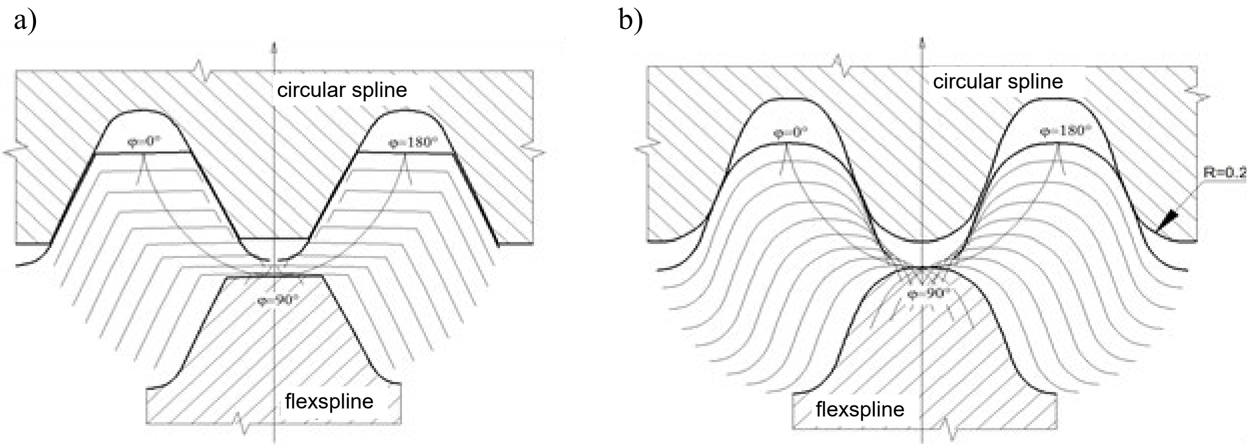

Fig. 4. Trajectory of the flexspline's tooth: a) for the theoretical outline, b) for the outline of the model obtained by 3D printing method.

While comparing the stages of tooth displacements of the theoretical and real outline, attention should be paid to a much greater space between the vertexes of the moving teeth in the second case. At the same time, for the angle of $\varphi=0^o$, in both cases there is a proper contact between the side surfaces of the teeth, because the measured differences in tooth width on the theoretical and physical models were not significant. Finally, it should be noted, keeping in mind the specific nature of harmonic drive working, that the deviations of the tooth outlines presented on the flexsplines do not adversely affect the quality of its work. Differences between the reference profile and the real one obtained using the FEM / MEM method concern mainly the rounding of tooth tips, which can be even a beneficial phenomenon. New technological possibilities, appearing along with methods of rapid prototyping, allow for the search of new tooth outlines that can positively influence the improvement of work quality and load capacity of harmonic drives.

Summary

The 3D printing method allows for a quick and easy preparation of components of a functional prototype of a harmonic drive. The additive building process of a model is particularly advantageous in the case of a flexspline with an extremely complex shape. The conducted contact measurements, using a coordinate machine, enabled the analysis of the geometric accuracy of gear wheels manufactured using the FDM/MEM method. A slight discrepancy between the physical models and their theoretical counterparts is visible. The problems concerned the mapping of the outer corners of the prototypes made with the 3D printing method. However, in the case of the analyzed harmonic drive, where even several tooth pairs stay in the meshing, the accuracy of a single tooth profile is not a key issue. Constancy of the scale or width of subsequent grooves and teeth are much more important parameters. These parameters were also checked by measuring the rim gear in the cross-section. The obtained results indicate high accuracy of gear wheel models in this range. The determined average values of the width of subsequent teeth and scale differ by no more than 2% from the theoretical values. This allows for a very good evaluation of the accuracy of physical models of gears made using 3D printing. Positive assessment in the area of key geometric parameters allows for the use of a prototype of a harmonic drive in bench tests.

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