Use of rapid prototyping technology in complex plastic structures
Part II. Impact of operating conditions on functional properties of polymer harmonic drives

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Abstract: The influence of operating conditions on physical and mechanical properties of tooth surface in the flexspline of a harmonic drive was investigated. 3D printed test models were made from poly(acrylonitrile-*co*-butadiene-*co*-styrene) (ABS) copolymer and from poly(lactic acid) (PLA) and subjected to the accelerated UV aging test and to bench tests. Measurements of hardness, Vicat softening point and atomic force microscopy (AFM) analysis were performed in order to determine the properties of the teeth surface in the gear wheels. Furthermore, the degree of degradation of the plastics was determined with IR spectroscopy. It was found, that the ambient conditions and exploitation of harmonic drives do not affect the value of softening point and hardness. On the other hand, the AFM analysis indicated that the sides of teeth were smoother as a result of their cooperation. The values of *Ra* parameter in the areas examined decreased from 110.0 to 54.6 nm and from 23.9 to 17.0 nm for the gear wheels made of ABS and PLA, respectively. Furthermore, the Derjaguin-Muller-Toporov modulus (DMT) of surfaces was also decreased from 10.0 to 3.0 GPa and from 4.5 to 2.2 GPa in the gear wheels made of ABS and PLA, respectively. The AFM imaging provide evidence for destructive effects of UV radiation and elevated humidity, confirmed by IR spectroscopy.

Keywords: harmonic drive, ABS, PLA, functional properties, AFM, degradation, rapid prototyping.

Zastosowanie technologii szybkiego prototypowania skomplikowanych konstrukcji z tworzyw polimerowych
Cz. II. Wpływ warunków pracy na właściwości funkcjonalne polimerowych napędów harmonicznych

Streszczenie: Badano wpływ warunków eksploatacyjnych kół podatnych zębatej przekładni falowej na właściwości fizyczne oraz mechaniczne powierzchni zębów. Z zastosowaniem druku 3D z kopolimeru poli(akrylonitryl-*co*-butadien-*co*-styren) (ABS) oraz polilaktydu (PLA) wykonano modele badawcze, które poddano przyspieszonemu starzeniu promieniami UV, przeprowadzono też badania stanowiskowe. Właściwości zębów otrzymanych kół zębatych charakteryzowano na podstawie twardości i temperatury mięknienia Vicata, analizy powierzchni z wykorzystaniem mikroskopii sił atomowych (AFM) oraz stopnia degradacji tworzywa oznaczonego za pomocą spektroskopii IR. Stwierdzono, że warunki środowiskowe oraz eksploatacja zębatej przekładni falowej nie wpływają w istotnym stopniu na wartości temperatury Vicata i twardość powierzchni zębów. Analiza AFM wykazała, że w wyniku współpracy powierzchnia zębów się wygładziła. Średnia wartość chropowatości *Ra* kół zębatych wykonanych, odpowiednio, z ABS i PLA zmniejszyła się ze 110,0 do 54,6 nm oraz ze 23,9 do 17,0 nm. Ponadto, moduł Derjaguina-Mullera-Toporova (DMT) powierzchni elementów wykonanych z ABS oraz PLA również się zmniejszył, odpowiednio, z 10,0 do 3,0 GPa oraz z 4,5 do 2,2 GPa, co wskazuje na destrukcyjny wpływ promieniowania UV i podwyższonej wilgotności, potwierdzony metodą spektroskopii IR.

Słowa kluczowe: napęd harmoniczny, ABS, PLA, właściwości użytkowe, AFM, degradacja, szybkie prototypowanie.

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Rapid prototyping methods (RP) are among the fastest growing manufacturing technologies. Owing to their large diversity they are applied in numerous branches of industry, and the wide assortment of the materials used makes it possible to satisfy a variety of needs. RP techniques can be used in producing demonstration models, where the main focus is on the appearance of the specimen. The method is frequently applied in producing functional prototypes of mechanisms to be used in field tests and endurance tests. It is also a common practice that RP methods are used in manufacturing of finished products if the related durability and reliability requirements are not very high. To verify feasibility of a selected RP method for producing a specific structural part it is necessary to perform in-depth analyses. While designing such a part it is necessary to take into account the limitations of the technology and the materials, and to choose a production technique taking into account the expected properties and precision of the finished product.

If we aim to produce functional models of harmonic drives, it is particularly important to perform analysis of opportunities and risks resulting from the choice of one of the rapid prototyping methods. The structure of this type of gear is very complex and the flexspline, designed as a thin-walled barrel, is a component which poses a lot of problems both at the stage of designing and during production. In order to make a flexspline using conventional machining methods it is necessary to apply special pivots and clamping fixtures. Special attention is needed during the process of cutting the small-module toothed rim, because of the height of the teeth, as a rule below 1 mm. Each manufacturing error affects the geometry of the teeth, leading to incorrect operation of the drives which are used mainly because of their excellent kinematic accuracy. Rapid prototyping techniques provide many new options which make it possible to take a novel approach to designing gear wheels, drawing on the current state of knowledge.

With regard to production of flexsplines for harmonic drives, there are a lot of expectations connected with the use of additive techniques, such as modeling with liquid materials. This method of producing gear wheels would make it possible to give up the special tooling required by conventional techniques. In such methods as fused deposition modeling/melting and extrusion modeling (FDM/MEM), with one or two printer nozzles, the material is added to the model in consecutive layers, whereby it is possible to achieve specimens with highly complex exterior shapes and any degree of internal solidity. Flexspline has constant profile in a large part of its structure, so attempts to use additive techniques in this case are absolutely justified. Physical models produced using rapid prototyping methods present sufficient geometric accuracy [1–3], and related evidence was also reported for gear wheels of harmonic drives [4, 5]. It is, however, necessary to determine whether materials applied by RP methods are feasible for use in components of harmonic drives. Previous scientific work on the use of polymers in the incremental methods focuses on the technological aspects [6–8] and polymer modification [9–11]. On the other hand, publications describing the properties of gear wheels made of metals often describe the properties of the surface layer of cooperating elements and the effect of friction on the strength of teeth [12–15]. Given the fact that drives of this type are commonly used in regulation and control mechanisms in robotics, in optical systems and in measuring instruments, it is necessary to investigate the influence of operating conditions for physical and chemical properties of polymeric gears. The present study is designed to continue research conducted at the Department of Mechanical Engineering and the Department of Polymer Composites and focusing on application of polymer materials in production of gear wheels [16]. The current study investigated the effects of operating conditions in the mechanical and physicochemical properties as well as the structure of the surface of teeth, made of poly(acrylonitrile-*co*-butadiene-*co*-styrene) (ABS) copolymer and from poly(lactic acid) (PLA), in a flexspline of a harmonic drive.

EXPERIMENTAL PART

Materials

Two types of prototype harmonic drives were prepared, using the copolymer ABS [poly(acrylonitrile-*co*-butadiene-*co*-styrene)] as well as PLA [poly(lactic acid)] from Hbot3D Filaments.

Preparation of specimens

A prototype of a complete harmonic drive, comprising flexspline, circular spline and wave generator, was 3D printed using UP Plus 2, and MEM (melted extrusion manufacturing) technique, with the models arranged in such a way that subsequent layers were added in the direction of the main axis.

All the models were designed to have complete internal solidity and to be printed using a single layer of 0.1 mm, the lowest height offered by the machine. Five specimens of flexsplines were made from each of the materials to enable measurements during different stages of harmonic drive operation and in varied ambient conditions.

Methods of testing

Simulation study testing operation of the prototype harmonic drives was carried out in a specially designed measuring station, whose layout is shown in Fig. 1.

The flexspline, circular spline, and wave generator were assembled in the same way as in a real-life drive, and mounted onto a steel plate, which ensured adequate rigidity of the whole structure. The input shaft of the drive was connected to a powering device, which enabled simulation of real-life operation of the system. It was assumed

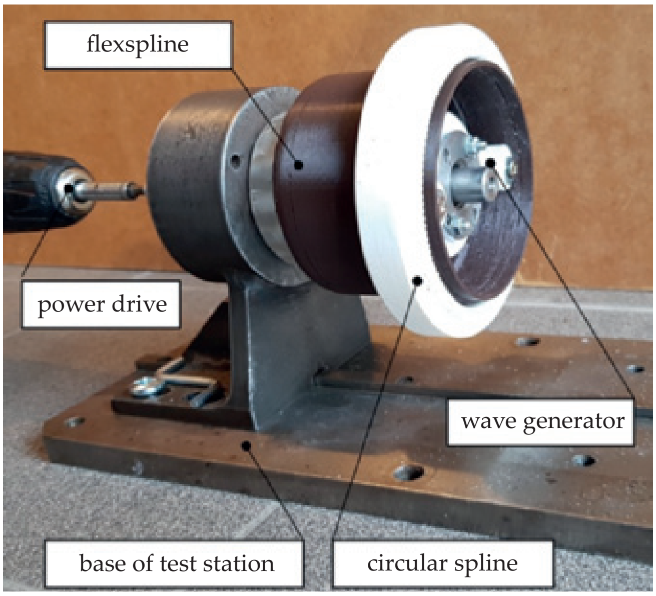

Fig. 1. Station designed for testing the harmonic drives

that the drive would eventually be mounted in a control mechanism, *e.g.*, to determine the position of a measuring arm. Given this it was assumed the drive would operate in a cyclic manner, with the generator shaft rotational speed of 300 rpm. During the tests, loading was applied in both directions of rotation for 30 seconds, to be followed by an interval of 15 seconds. This cycle of operation was repeated 150 times, after which the drive was disassembled and the measurements were performed.

Testing of accelerated aging in fragments of gear wheels was conducted in the climatic test chamber XENONTEST ALPHA + from ATLAS, equipped with a xenon lamp. The aging test was conducted in conformity with PN-EN ISO 4892-2 in the samples cut out after the bench tests, and subjected to UV radiation for 100 hours and to 55 % humidity. Irradiation in the aging chamber was applied as defined by cycle B. Cycle B involves irradiation with UV for 4 hours at 60 °C with lamp intensity of 0.71 W/m^2 and wavelength of 313 nm. Irradiation continuing for 4 hours was followed with water vapor condensation for 4 hours, at 50 °C. This was followed with irradiation, *etc*.

Rockwell hardness was determined in the side surfaces of the teeth, using a durometer ZWICK 3106, in accordance with EN 10109-1. The final result was the arithmetic mean of at least 10 measurements.

Vicat softening point was determined in the side surfaces of the teeth, in compliance with PN-EN ISO 306, and method B120 was used in ABS samples and method A120 in PLA samples.

In order to determine wear-related effects in the gear wheels, resulting from the operating conditions, atomic force microscopy (AFM) was applied in order to scan the surfaces of teeth in the samples, before and after the cycle of operation and following accelerated aging; for this purpose the technique of quantitative nanomechanical property mapping (QNM) was applied. The examinations were performed with Nanoscope VIII from Bruker, using RTESPA scanning needle, with resonant frequency of 300 kHz and constant elasticity of 20–80 N/m. Images were recorded at a scanning speed of 0.5 kHz and resolution of 256 lines, and were then analyzed using Nanoscope Analysis software.

FT-IR analysis of the samples was performed using Nicolet 6700 spectrophotometer, manufactured by ThermoScientific (USA), equipped with ATR module with a diamond accessory. The measurements were carried out in the range of 550–4000 cm^{-1}, with 48 scans and resolution of 4 cm^{-1} for each sample. The spectra were subjected to advanced ATR correction, atmospheric correction, and baseline correction.

RESULTS AND DISCUSSION

IR analysis

In the obtained spectrum (Fig. 2) we observe characteristic bands typical for ABS in the wave number 2240–2220, 960–910 and 800–690 cm^{-1} that indicate the presence of acrylonitrile, butadiene and C-H aromatic binding, respectively [17]. In turn, based on the spectra and the intensity of the characteristic bands it was determined that exploitation of the gear wheels resulted in degradation of the material on the tooth surface. This is reflected by the occurrence of a wide band originating from hydroxyl group at the wavelength of 3370 cm^{-1} and from carbonyl group at 1731 cm^{-1}. Furthermore, the absorbance bands in virgin ABS, corresponding to deformation of C-H in hydrogen atoms attached to alkenic carbons at 966 cm^{-1} in 1,4-butadiene units and at 910 cm^{-1} in 1,2-butadiene units, were found to decrease in the case of the molder after aging [18–20]. Likewise, the band associated with valence vibrations of vinyl group contained in 1,4-butadiene disappeared in the case of a sample subjected to aging.

In the case of the PLA gear wheels, the change in the structure of the polymer, resulting from degradation of the material following operation of the drive in real-life conditions, is not as distinctive as in the ABS part, since the intensity of the band associated with the presence of OH groups at 3324 cm^{-1} is significantly lower (Fig. 3). On the other hand, the carbonyl band visible at 1755 cm^{-1} is also observed in the case of a non-aged sample, as a result of which the change in the peak intensity is also small. However, at 760–700 cm^{-1}, also characteristic for C=O group, it is possible to observe increased intensity of the band, possibly reflecting degradation of the material [21]. Furthermore, in the samples subjected to aging there was also greater intensity of the band corresponding to asymmetrical valence vibrations of -CH- group at 1360 cm^{-1}. Additionally, the appearance of the wide band at 799 cm^{-1} possibly linked with formation of peroxide structures may reflect degradation of the material [22–24].

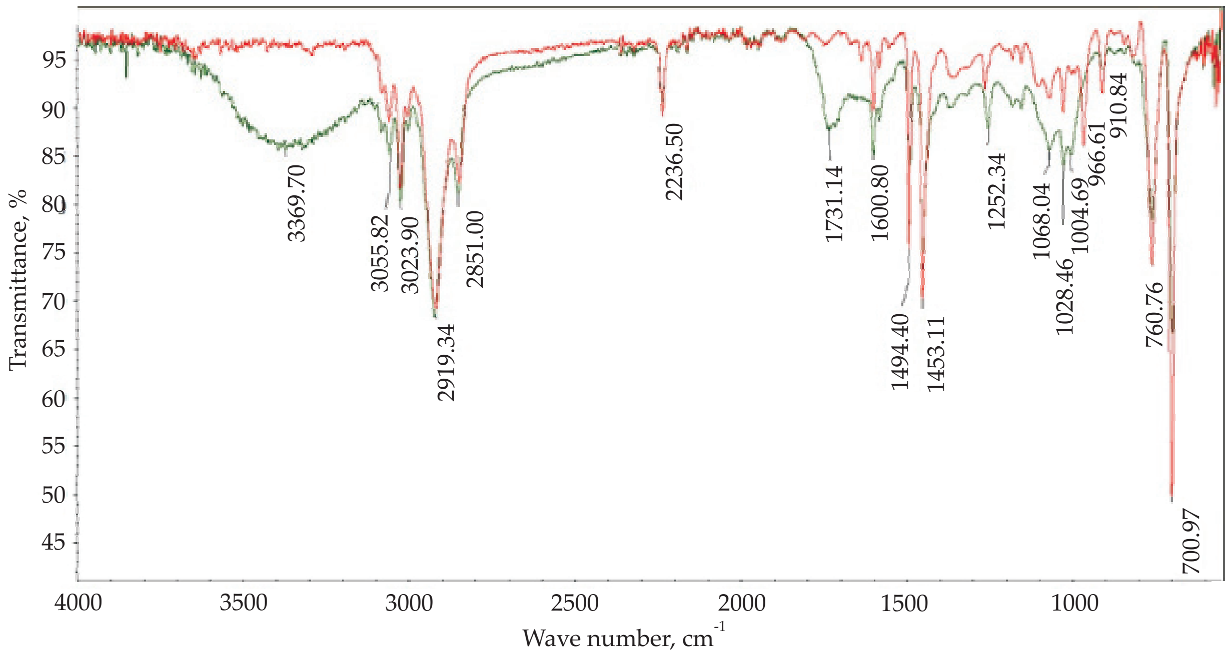

Fig. 2. IR spectra of the teeth in the gear wheels made of ABS: the surface before aging – the red line, the surface after aging – the green line

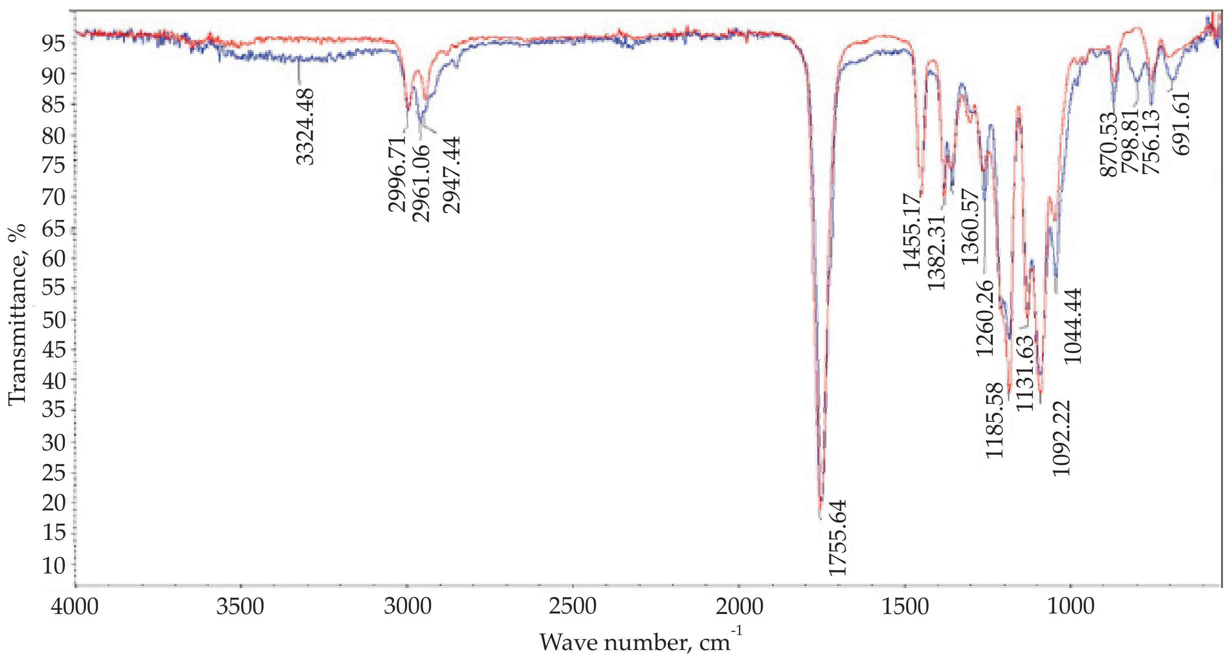

Fig. 3. IR spectra of the teeth in the gear wheels made of PLA: the surface before aging – the red line, the surface after aging – the blue line

T a b l e 1. Hardness and Vicat softening point identified in the side surface of teeth of a flexspline before and after test operation

Polymer	Properties			
	Before operation		After operation	
	Hardness N/mm²	Vicat softening point °C	Hardness N/mm²	Vicat softening point °C
ABS	21.8 ± 2.1	89.1 ± 1.1	23.3 ± 1.6	90.5 ± 0.7
PLA	52.4 ± 5.6	51.4 ± 2.5	53.4 ± 6.5	51.8 ± 1.2

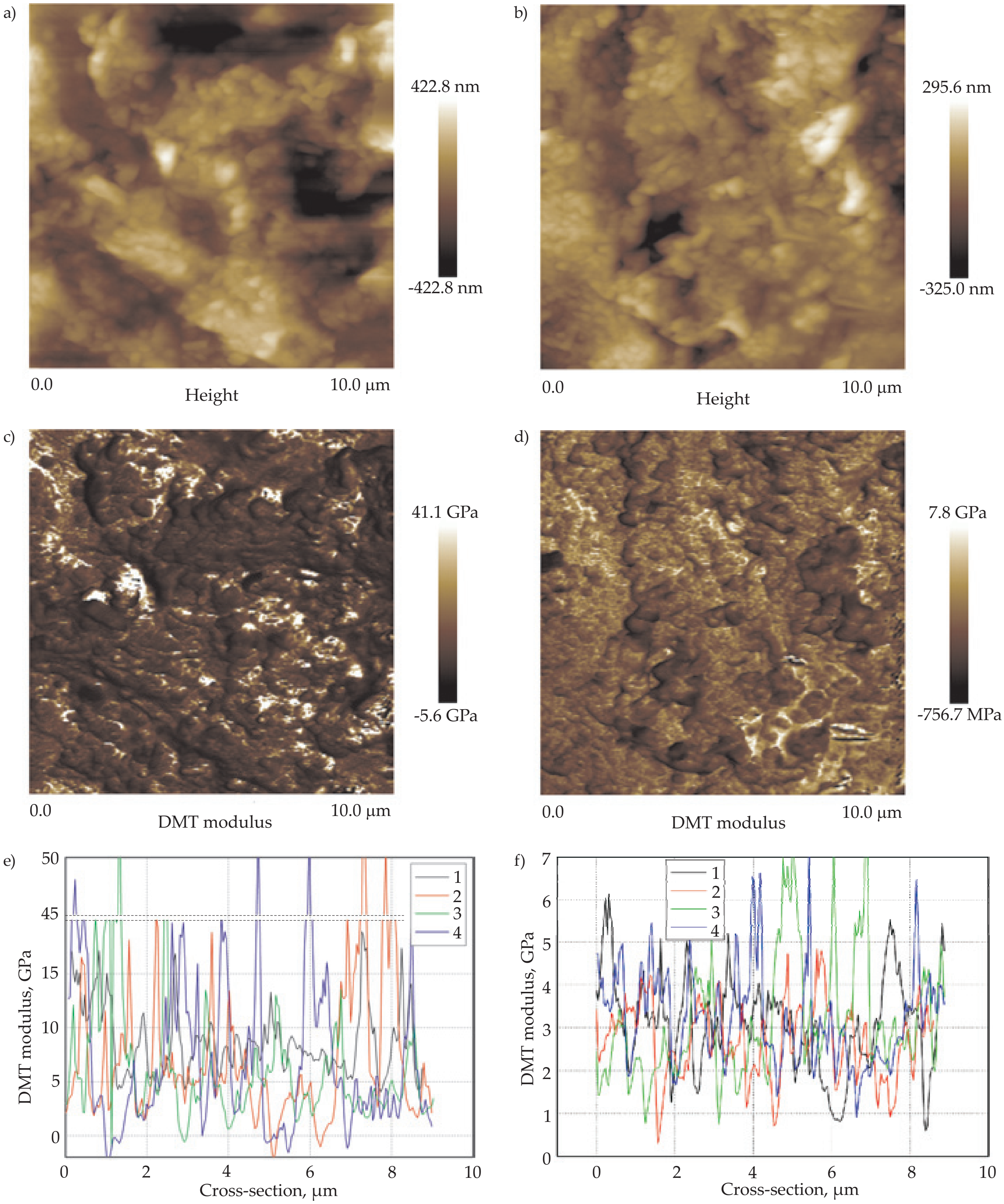

Fig. 4. AFM images showing topography and distribution of Young DMT modulus in the surface of gear wheel teeth made of ABS: a, c, e) before the cycle of operation and accelerated aging, b, d, f) following 150 cycles of operation and the aging procedure

Hardness and softening point

Analysis of the values representing hardness and Vicat softening point shows that the 3D printed parts made of ABS and PLA are characterized by lower values of these parameters compared to data reported in the literature for injection molds. This results from the heterogeneous structure characteristic for MEM technique.

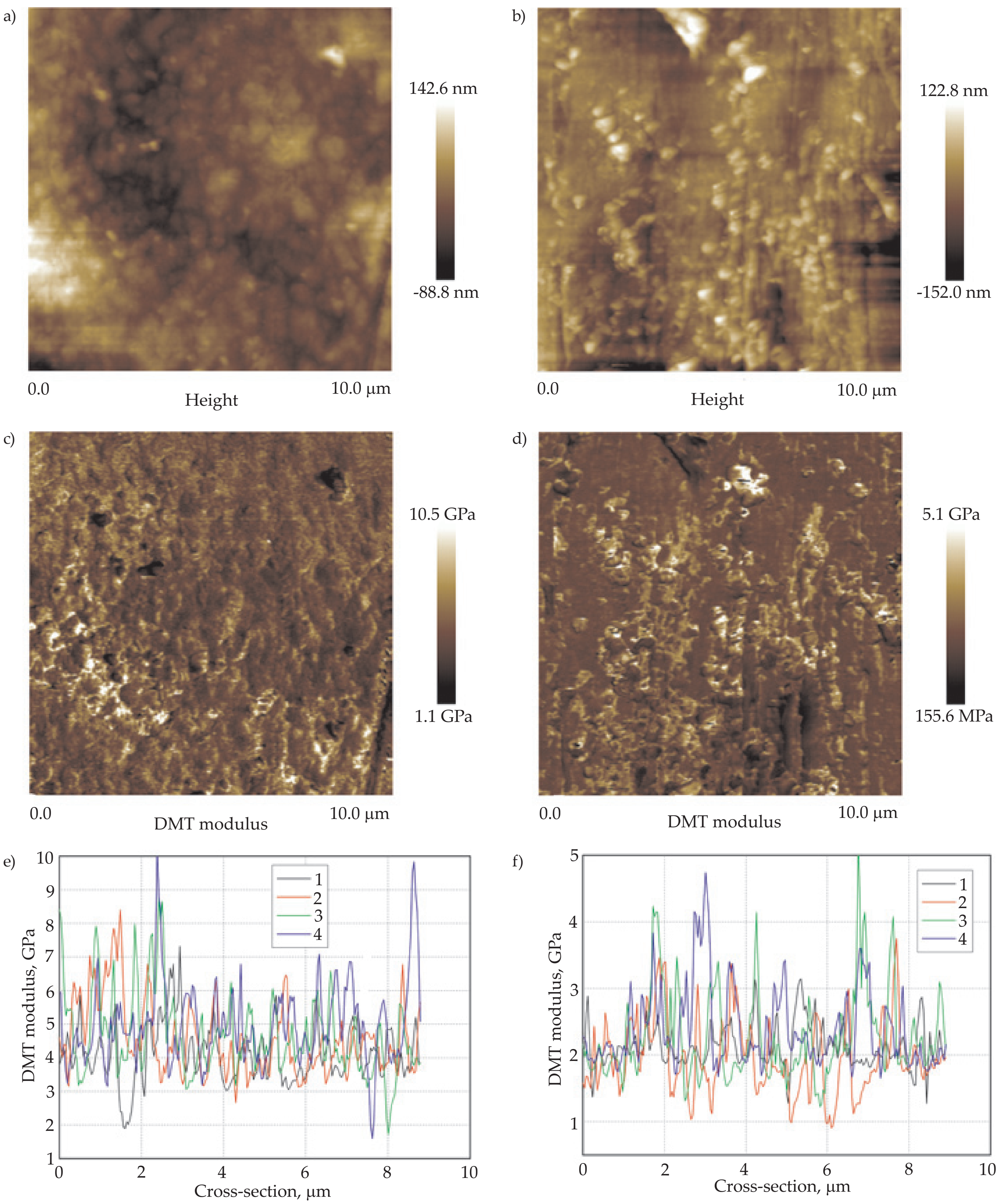

Fig. 5. AFM images showing topography and distribution of Young DMT modulus in the surface of gear wheel teeth made of PLA: a, c, e) before the cycle of operation and accelerated aging, b, d, f) following 150 cycles of operation and the aging procedure

A comparison of the materials applied shows that greater Rockwell hardness was obtained in the gear wheels made of PLA (Table 1). Interestingly, irrespective of the type of material applied, hardness in the side surface of the teeth did not change following exploitation of the gear wheels. Similar effect was observed with regard to softening point, which did not change following a cycle of operation and aging.

AFM analysis of teeth surface

AFM imaging was applied to examine topography and distribution of reduced Young's modulus (according to Derjaguin-Muller-Toporov [DMT] modulus) in the teeth surface of gear wheels made of PLA and ABS [25]. The registered images of topography show that, following a cycle of operation and accelerated aging procedure, the tooth surface was smoother (Figs. 4a, 4b and 5a, 5b). In the ABS gear wheels the mean roughness *Ra* of the tooth surface decreased twofold, compared to the initial value (110 nm); conversely in the PLA gear wheels there was only a minor change in roughness. Its mean value in the surface of the teeth made of this polymer was 23.9 nm, while the analysis of the tooth topography following the cycle of operation showed that the value decreased to 17.0 nm. Changes in the surface properties are also visible in the images representing the distribution of DMT modulus (Figs. 4c, 4d and 5c, 5d). Its value was decreased following the cycle of operation and the accelerated aging procedure.

Analysis of the cross-section of the surface shows that the mean value of the modulus decreased from 10 GPa to 3 GPa and from 4.5 GPa to 2.2 GPa in the gear wheels made of ABS and PLA, respectively (Fig. 4f and Fig. 5f). The findings related to the surface structure of flexspline teeth suggest that they are partly worn out during operation and due to activity of external factors. Analysis of the materials applied shows that smaller changes in the surface morphology, *i.e.*, roughness and DMT module, were observed in the gear wheels made of PLA, which is linked with the greater rigidity of this material compared to ABS.

CONCLUSIONS

The research findings presented in the article show in which way environmental conditions affect selected qualitative and strength parameters in machine parts made of polymer materials. Harmonic drive, selected for the tests, is characterized by small unit loading per one tooth, therefore it can be manufactured from non-metallic materials. Furthermore, the fact that the shape of flexspline is not typical provides an encouragement for applying additive methods, such as MEM, in producing this type of gear wheel.

All the samples presented similar hardness, despite the fact that loading was applied to the drives, and the parts were subjected to accelerated aging process; this is positive finding related to these materials. However, the results identified for harmonic drive parts produced using MEM technique were significantly lower than in the case of components manufactured by injection moulding.

Likewise, the findings show that ambient conditions and exploitation of harmonic drives do not affect the value of softening point. The relevant values did not change significantly, either in ABS or in PLA parts, during the entire cycle of measurements.

The simultaneous small increase in the softening point and in hardness may result from the wearing-in of the harmonic drive parts cooperating with one another. This may also be reflected by the results of AFM imaging used in the measurements of the surfaces. The obtained evidence shows that the sides of teeth were smoother as a result of their cooperation. In the case of both ABS and PLA, following the operation cycle and the aging process, the values of *Ra* parameter in the areas examined were decreased, from 110.0 to 54.6 nm and from 23.9 to 17.0 nm, respectively. However, the reduced values of DMT modulus (by 7.0 and 2.3 GPa in the gear wheels made of ABS and PLA, respectively), also identified using AFM imaging, provide evidence for destructive effects of UV radiation and elevated humidity. Following the cycle of exploitation, the harmonic drive parts made from the two materials in question were characterized by lower durability than at the start.

Analysis of IR spectra also confirmed destructive effects of ambient conditions and meshing of the working surfaces of teeth in the structure of the relevant materials. Exposition of a harmonic drive to long-lasting operation in the simulated conditions may lead to significant decrease in its durability.

The current findings allow a conclusion that rapid prototyping methods, including MEM technique, are highly suitable for making prototypes of various machine parts for research purposes. Additive techniques enable rapid and cost-effective production of complex models, such as flexpline. Materials applied in rapid prototyping methods, *e.g.*, ABS and PLA, are sufficiently rigid and durable for the needs of prototypes used in research.

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