The geometric accuracy analysis of polymer spiral bevel gears carried out in a measurement system based on the Industry 4.0 structure

Jadwiga Pisula[1)]

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Abstract: The paper presents geometrical accuracy tests of polymer spiral bevel gears. The change in geometry was quantified with reference to research models produced by incremental methods: FDM (fused deposition modeling), SLS (selective laser sintering), DLP (digital light processing) and PolyJet. Model geometry verification was made basing on the INDUSTRY 4.0 philosophy using the Klingelnberg P40 coordinate measuring machine (CMM) operating in an integrated network system. The graphs show deviations of selected parameters defining the geometry of the teeth. Analysis of the obtained results was used to select the appropriate printing technology and to improve the quality of the polymer gears. The highest 11th accuracy class of the spiral bevel gear teeth, determined according to DIN 3965, was obtained for models manufactured in PolyJet additive technology.

Keywords: polymer materials, gears models, coordinate measuring machine, geometrical accuracy.

Analiza dokładności geometrycznej polimerowych stożkowych kół zębatych realizowana w układzie pomiarowym opartym na strukturze Przemysł 4.0

Streszczenie: Zbadano dokładność geometryczną polimerowych zębatych kół stożkowych o kołowej linii zęba. Oceniano ilościowo zmianę geometrii w odniesieniu do modeli badawczych wytwarzanych metodami przyrostowymi: osadzania topionego materiału FDM (ang. *fused deposition modeling*), selektywnego spiekania laserowego SLS (ang. *selective laser sintering*), wykorzystania cyfrowej projekcji światła DLP (ang. *digital light processing*) oraz PolyJet. Weryfikację geometrii modeli wykonano, opierając się na filozofii Przemysł 4.0, z wykorzystaniem współrzędnościowej maszyny pomiarowej (CMM) P40 firmy Klingelnberg, pracującej w zintegrowanym układzie sieciowym. Na wykresach zilustrowano odchylenia wybranych parametrów definiujących geometrię uzębienia. Analiza otrzymanych wyników posłużyła do wyboru odpowiedniej technologii druku oraz poprawy jakości wykonania polimerowych kół. Najwyższą, 11 klasę dokładności uzębienia kół stożkowych o kołowej linii zęba, określoną wg normy DIN 3965, uzyskano w wypadku modeli wytworzonych w technologii przyrostowej PolyJet.

Słowa kluczowe: materiały polimerowe, modele kół zębatych, współrzędnościowa maszyna pomiarowa, dokładność geometryczna.

Using the rapid prototyping (RP) based on polymeric materials to make a physical product based on a 3D model obtained with the use of computer aided design (CAD) reduces the cost of manufacturing machine elements [1]. It is possible due to the elimination of the use of special instrumentation and multi-operability of production [2]. However, the possibilities of incremental technologies have their limitations [2], which include: selection of material with appropriate strength and surface structure, the potential of available printing devices in the context of the size of the model and obtaining a finished product within a given dimensional and geometric tolerance. The conducted research focuses on the selection of appropriate technological parameters of the additive process and optimization of the geometry of the source model (material shrinkage, support structures) in order to obtain maximum strength of the manufactured product and the appropriate geometric accuracy, roughness and surface topography of the product [3–6]. Parts made of polymer materials with additive methods are functional prototypes used to carry out experiments [7].

As research models, spiral bevel gears were chosen, which are characterized by the complex geometry of the teeth. The accuracy of the teeth and the base surfaces of the gears determine the uniformity of transferring move-

[1)] Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, Al. Powstańców Warszawy 8, 35-959 Rzeszów, Poland.
e-mail: jpisula@prz.edu.pl

ment through transmission [8, 9]. It is necessary to confirm the functionality of the gear. The parts were made with incremental technologies on selected printing devices, where it is possible to use specific materials. The tests were carried out on gears made in FDM technology (fused deposition modeling), SLS (selective laser sintering), DLP (digital light processing) and PolyJet modeling. The following materials were used: thermoplastic polymers (FDM), polyamide powder (SLS) and photopolymer resins (PolyJet and DLP).

The article assesses the geometrical accuracy of the manufactured polymer gears using the Klingelnberg coordinate measuring machine (CMM) P40. The machine P40 is one of the elements of the structure based on the idea of INDUSTRY 4.0 [10], which includes: 3D-CAD modeling system, data processing system, incremental and removal machining manufacturing systems, measurement system, data analysis system (Fig. 1).

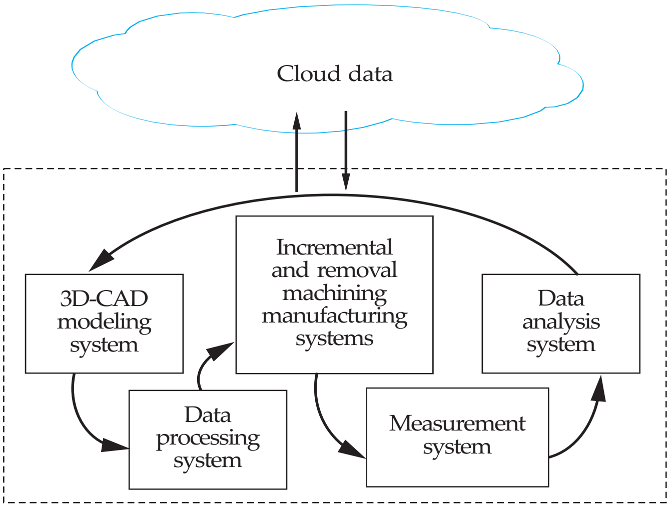

Fig. 1. The diagram describing the idea of INDUSTRY 4.0

A specialized program was used to measure and analyze the accuracy of the teeth of the spiral bevel gears. This is especially important because the program compares the geometry obtained from the measurement to the defined the base gear model. This allowed to: determine the capabilities of the printing device in terms of the accuracy of the geometry mapping, marking the areas of incompatibility of the model printed regarding to the base model, and as a result defining appropriate revisions about the model and its location on the working platform.

EXPERIMENTAL PART

Research models

The CAD models (Fig. 2) were the base for research models, which were obtained using a mathematical model for cutting such teeth [11, 12] and a special program KIMoS for designing bevel gears from Klingelnberg [13].

The KIMoS program determines the gear geometry and technological parameters of machining the teeth

T a b l e 1. Basic geometric data of reference gears

Symbol	Description	Value
Shaft angle	Σ	90°
Number of teeth – pinion	z_1	20
Number of teeth – gear	z_2	37
Pressure angle	α_0	20°
Outer transverse module	m_{te}	2.6 mm
Outer pitch diameter of pinion	d_{e1}	52.0 mm
Outer pitch diameter of gear	d_{e2}	96.2 mm
Face width	b	16.0 mm
Mean spiral angle	β	33°30′

of the gear and pinion according to a specific cutting method. In addition, the program defines the reference geometry of the gears needed to measure them by the Klingelnberg P40 measuring center [14]. The selected geometric data of the basic gears are given in Table 1.

Applied materials and incremental technologies

The following incremental technologies were used to make gear models: FDM, SLS, DLP and PolyJet. The use of a specific material is associated with the selected incremental technology. In addition, available printing devices also determine or significantly limit the choice of print material for models. Table 2 shows the details of the printing test models selected by incremental technology.

Four pairs of gears made in FDM technology were prepared for geometric analysis. The applied FDM technology consists creating parts by applying successive layers of semi-liquid, thermoplastic material. To minimize the deformations arising from the linear contraction of the material, the process takes place at a sufficiently high

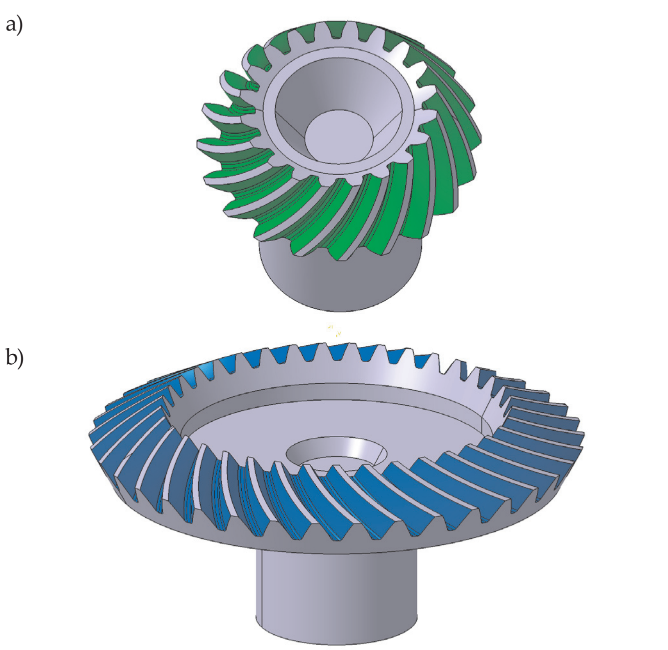

Fig. 2. The 3D-CAD nominal models: a) pinion, b) gear

T a b l e 2. Technologies, devices and materials used in particular research models

	 A	 B	 C	 D	 E	 F	 G
Incremental technology	PolyJet	MEM (FDM)	FFF (FDM)	SLS	FFF (FDM)	FFF (FDM)	DLP
Printing machine	OBJET EDEN 260V	UP Box Plus	Ultimaker 3 Extended	TPM Elite P3200	Prusa MK3	Prusa MK3	Vida
Firm	Stratasys®	Tiertime	Ultimaker	TPM	Josef Prusa	Josef Prusa	EnvisionTec
Fulfillment	100 %	20 %	20 %	100 %	20 %	20 %	100 %
Layer thickness	0.016 mm	0.15 mm	0.1 mm	0.15 mm	0.15 mm	0.15 mm	0.05 mm
Support/ postprocessing	Yes – special resin removed with water under pressure	Yes – the same material as the model, mechanically removed	Yes – material other than in the model, mechanically removed	No	Yes – the same material as the model, mechanically removed	Yes – the same material as the model, mechanically removed	Yes – the same material as the model, mechanically removed
The material in general	Photopolymer (acrylic- -polyester resin)	Copolymer (acrylonitrile- -butadiene- -styrene)	Polylactide [poly(lactic acid)]	Polyamide powder PA2200	Biopolyester [poly(lactic acid)/poly- hydroxy- alkanoate]	Thermoplastic polyester [poly(ethylene terephthalate)]	Photopolymer (acrylic resin methacrylic/ acrylic resin)
Name of the material of the model (support)	FullCure 720 (FullCure 705)	ABS	PLA	Precimid 1171	PLA/PHA	PET	E-Partial

temperature. Because the FDM name is reserved, companies that manufacture devices for printing in this technology use the names FFF (fused filament fabrication) and MEM (melted and extruded modeling). The article presents results for models made of thermoplastic materials: ABS, PLA and PET and on three printing devices (Table 2).

In SLS technology, in which the research model of the pinion and gear was made (Table 2), a layer of powdered polymer is applied to the printer's work table (PA2200 polyamide powder in the analyzed case). This powder is selectively melted, on contour and filling paths, in a specific shape of the layer, by a laser beam working in the long infrared band. The process takes place in a nitrogen atmosphere, so as not to burn the material and at high temperatures close to the melting point of the material.

Another printing technology used is the hardening of photopolymers using the projector's light was 3D DLP. The DLP prints are precise (accurate to several dozen microns), but they have a limit in the form of the size of the working field depending on the height of the layer. In the analyzed case, an acrylic resin with a thickness of 0.05 mm was used. However, the results for the gear research model were not taken into account, because due to the limited field of the work platform, the model had to be angled to it. This caused the model to be excluded from the analysis.

The models were also made in PolyJet technology, in which there is a layered application of photopolymer resins in a liquid form on the working platform, which are selectively hardened by UV light. Some resins are support material, others are model material. The model material in the analyzed case was FullCure 720 acrylic polyester resin, while the support material – FullCure 705 resin, which after hardening has a soft gel structure.

The research models were placed on the working platform with the tooth up (except for the gear made in DLP technology). The models were printed individually with the exception of SLS and PolyJet technology (pinion and gear were printed together). The applied layer height, the use of the support as well as the method of filling with the material are given in Table 2.

Measurement method of the models

Measurements of polymer spiral bevel gears made with incremental technologies were carried out on a Klingelnberg P40 coordinate measuring machine (Fig. 3). It is a measuring center, working in an automated cycle and designed for measuring gears (cylindrical, bevel and worm), toothed tools, crankshafts and camshafts, rotors and axially symmetrical elements.

To verify the accuracy of spiral bevel gears, special software for their measurement was used. Information

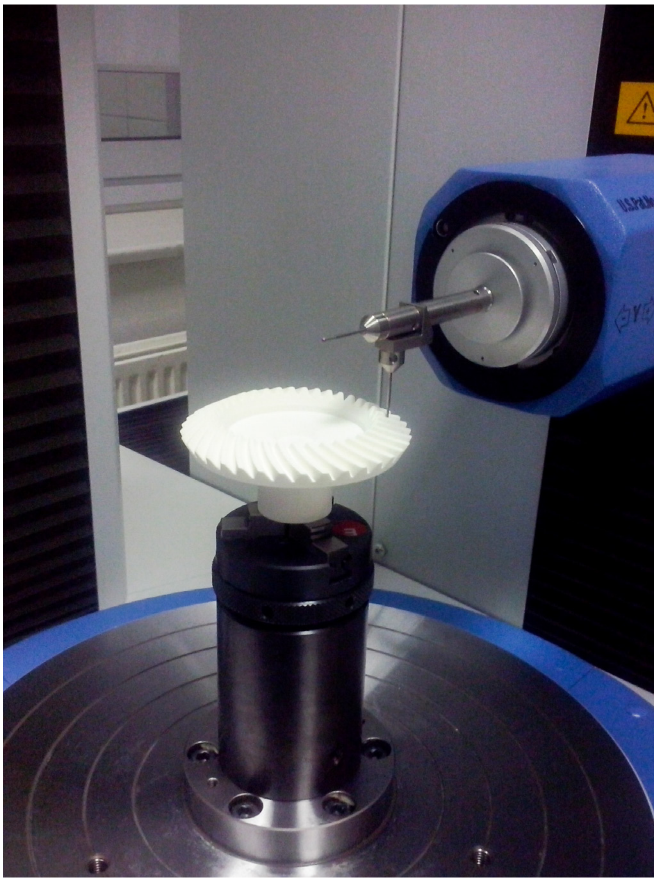

Fig. 3. Measurement of a spiral bevel gear made with the SLS method on the Klingelnberg coordinate measuring machine P40

on the measured geometry of the bevel gears is saved in the corresponding files on the server. The obtained results are a comparison of the measured geometry to the geometry of the reference model, which was achieved from the specialized KIMoS software that works with the P40 machine. This is particularly important when measuring spiral bevel gears, whose geometry of the teeth is complex [15, 16]. Coordinate measuring machine P40 allows obtaining high accuracy of measurement (Table 3).

T a b l e 3. Parameters used to measure the gears

Measuring machine	Klingelnberg Gear Measuring Centre P40
Probe System	K3D (M44)
Resolution	< 0.01 μm
Probe	D = 1.5 mm
Length measurement uncertainty	According to VDI/VDE 2617 $U_1 = 1.8 + L/250$ [μm] L – length in mm
Teeth to be checked (profile, lead)	3 teeth (evenly around the gear circumference)

The measurements took place in a laboratory room that ensured constant environmental conditions [17]. During the researches, two reference databases were used (cylindrical and face surface) appropriately selected for the pinion and gear. The same measuring tip was used for the pinion and gear models (Table 3). The results are average values from the measurement of three evenly positioned teeth on the perimeter of the research models. The study covered the topography of the tooth surfaces, the thickness in the normal cross-section and the mean tooth height. In addition, the pitch of the tooth, the pressure and the spiral angles as well as the tip and root cone angle were measured.

RESULTS AND DISCUSSION

The tests were performed in order to determine the accuracy of the polymer spiral bevel gears made by selected incremental technologies. The results of gear teeth measurement, performed on a P40 coordinate measuring machine, are presented below.

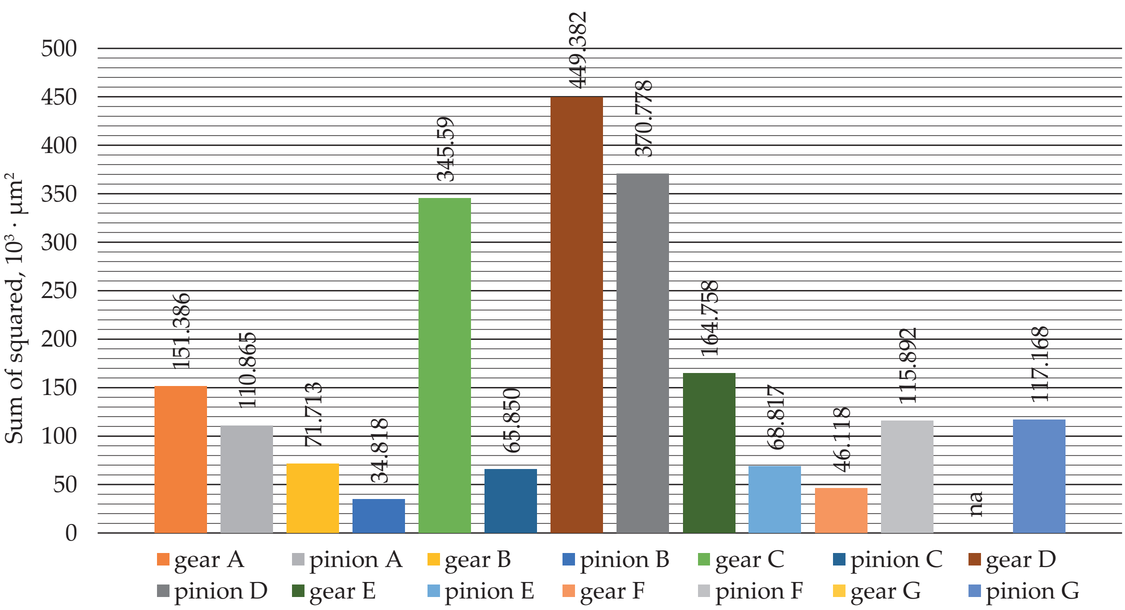

Fig. 4. Comparison of the average deviations of the topography of the tooth surfaces for individual research models

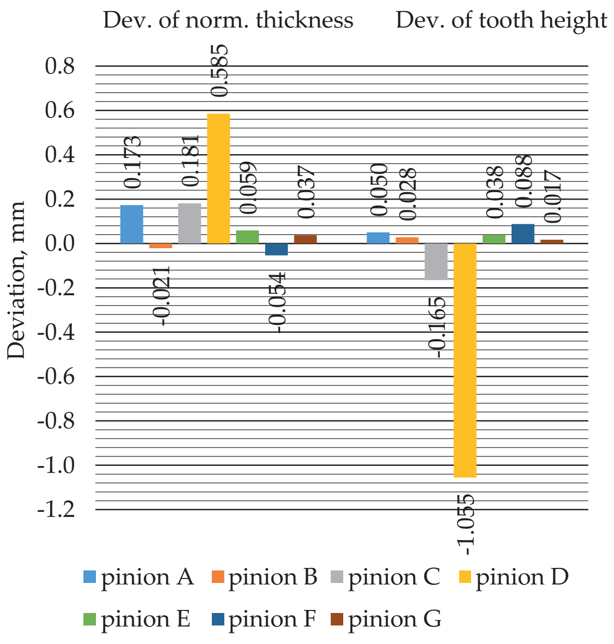

Fig. 5. Comparison of average deviations of normal thickness and mean tooth height for individual research models of pinions

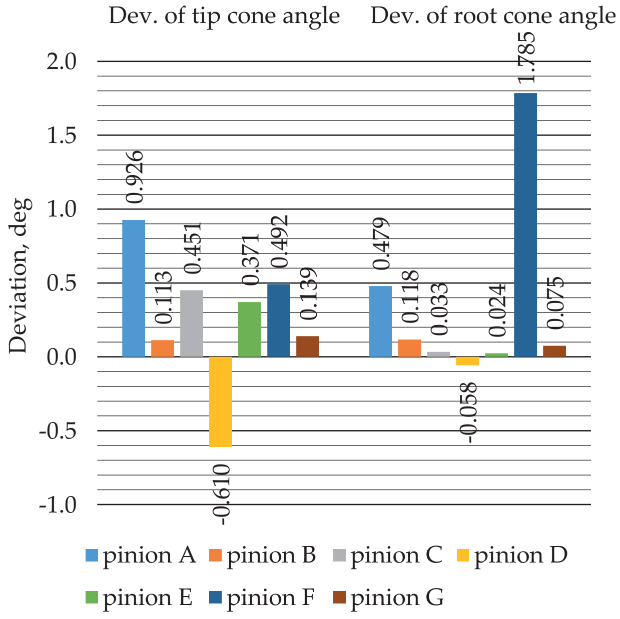

Fig. 6. Comparison of deviations of tip and root cone angles for individual research models of pinions

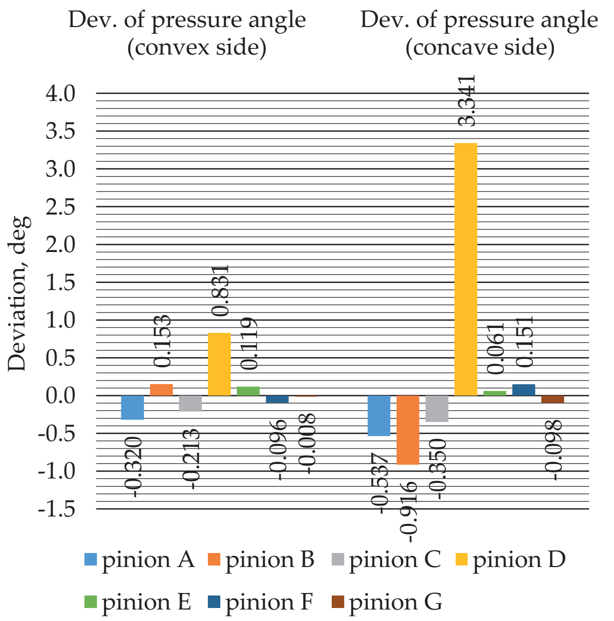

Fig. 7. Comparison of deviations of tooth pressure angles for convex and concave sides for individual research models of pinions

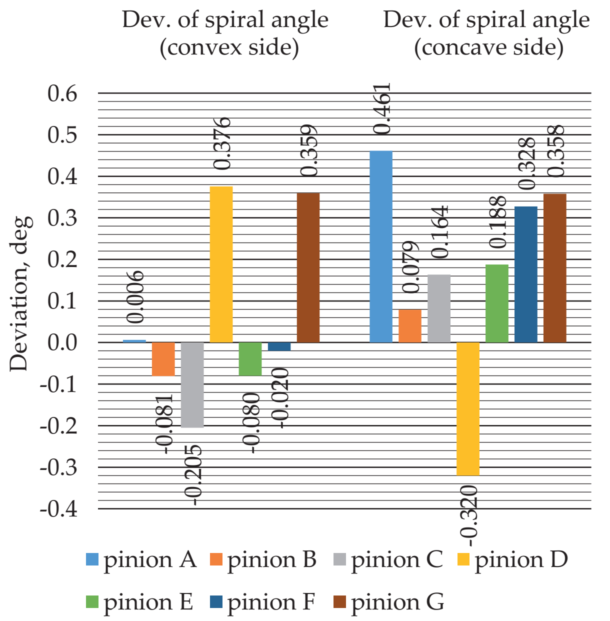

Fig. 8. Comparison of deviations of tooth spiral angles for convex and concave sides for individual research models of pinions

Figure 4 presents the results from the measurement of topography of teeth of pinions and gears with its average deviations for three teeth. The deviation of the tooth surfaces is given by the parameter which is the sum of squared position deviations for the measuring point grid, which was evenly applied to the tooth surfaces, from the reference surfaces. In the analyzed case, a 9 × 7 point grid was used. On the basis of the graph presented in Fig. 4, the largest topography deviation was obtained for models D made with SLS technology. The graphs of the topography of the tooth surfaces, which were not published in the article (due to their quantity), show that only in the case of models A made according to PolyJet and models G made according to DLP technology, the diagrams have a determined distribution of deviations on the tooth surfaces. Models made in other technologies have a disordered topography. The graphs show the disorders associated with stepping on the head "bumps" created during the modeling process. The graphs show disorders resulting from hits the measuring head with "bulges" created during the

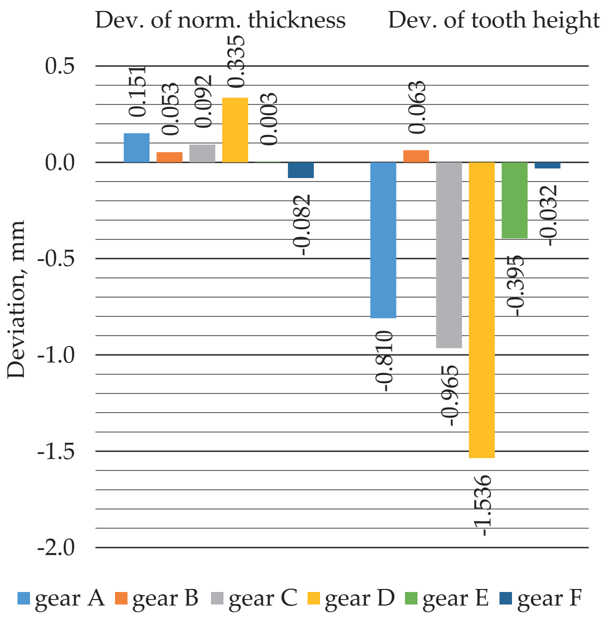

Fig. 9. Comparison of average deviations of normal thickness and mean tooth height for individual research models of gears

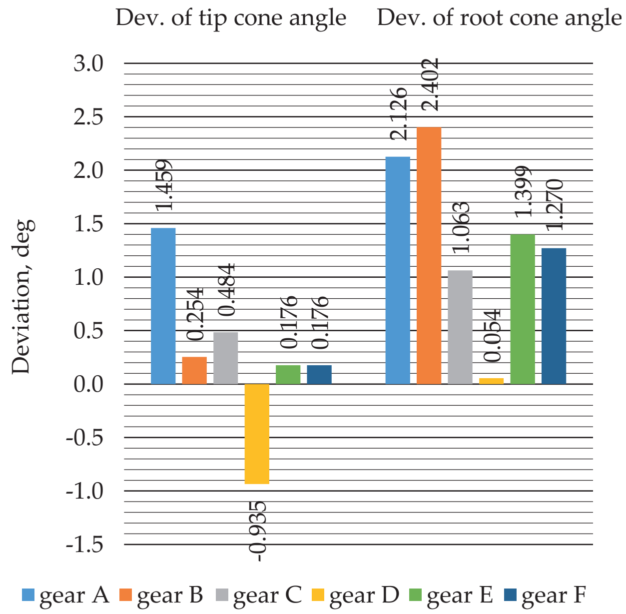

Fig. 10. Comparison of deviations of tip and root cone angles for individual research models of gears

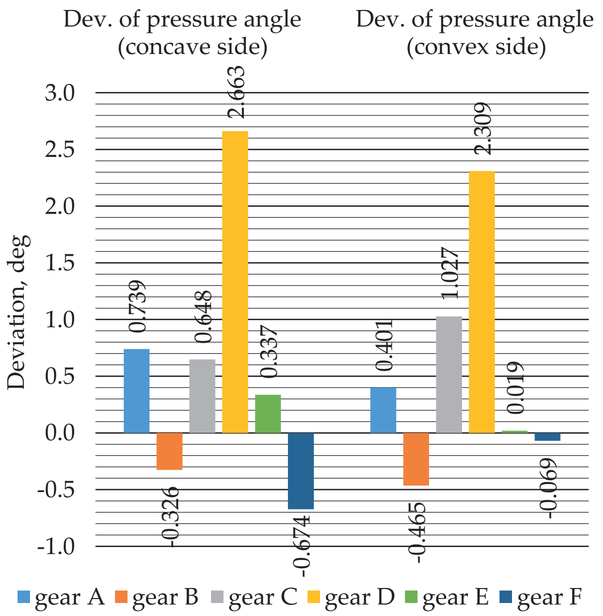

Fig. 11. Comparison of deviations of tooth pressure angles for convex and concave sides for individual research models of gears

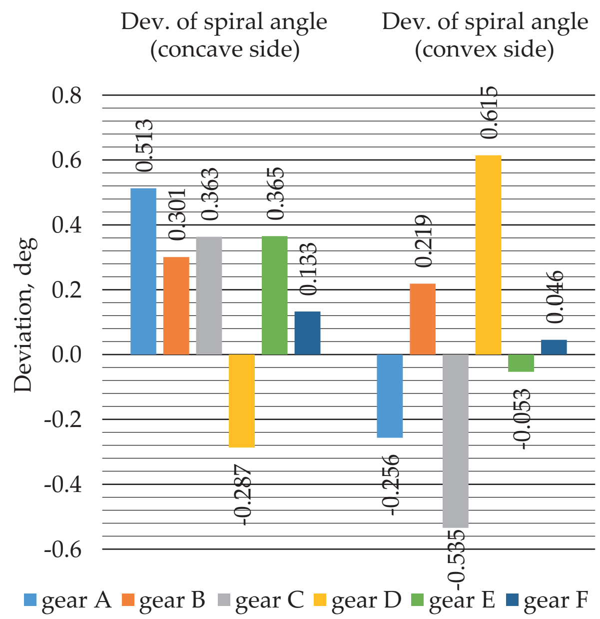

Fig. 12. Comparison of deviations of tooth spiral angles for convex and concave sides for individual research models of gears

process of printing models. Topography of the tooth of the pinion made with DLP technology is characterized by the uniformity of the distribution of deviations with the fact that on the convex side of the toe tooth of the pinion the deviations are negative (max. -20.6 μm) and gently pass towards heel tooth into positive deviations (max. 83.3 μm). On the concave side of the tooth from the toe tooth of the pinion the deviations are positive (max. 28.4 μm) and they pass into negative deviations (max. -65.0 μm) on heel tooth. The topography of the pinion on the concave side of a teeth made in the PolyJet technology is similar, with the difference that the deviations from the toe tooth are larger than those achieved on the model with DLP (max. -99.4 μm) and smaller on the heel tooth (max. 43.1 μm). The topography of the pinion on the convex side of the tooth, made by the PolyJet technology, has the shape of symmetrical lengthwise crowning with asymmetrical profile crowning and reaches the maximum deviation values at the root of the tooth (max. -30.8 μm of the toe tooth, max. -30.4 μm on the heel tooth).

Figures 5–8 relate to the measurement results obtained from the pinion test models, while Figs. 9–12 relate to the gear test models. For almost all technologies except for models printed with FFF technology (FDM), a positive value of tooth thickness deviation, *i.e.*, material allowance (Fig. 5, Fig. 9) was achieved. The most accurate thickness was imitated on models made of ABS and PLA/PHA. In the case of the height of the teeth measured in the middle of the tooth width, there is no similarity between the models of pinions and gears. Gears in most cases (except for made of ABS) have a height lower than assumed, while models of pinions have a height higher, except for those printed from PLA (FFF) and polyamide powder (SLS).

In the case of the tip cone angle of the pinion, without SLS model, the measured values of the angles are larger than the assumed angle on the reference model and they do not exceed 1 deg (Fig. 6). A similar relation is observed for the tip cone angle of the gear models (Fig. 10). The measurement of the root cone angle pinions is analogous. Also these angles are greater than the nominal value (except for the model made in SLS technology) (Fig. 6). For gear models, all root cone angles are larger than its nominal value and range from 0.054 deg (SLS) to 2.402 deg (MEM ABS material) (Fig. 10). The values of deviations for the pressure angles of the convex side of the tooth of the pinion oscillate near the nominal value of the pressure angles, with the exception of the model printed in the SLS technology. While for the concave side, the deviation values increase, especially those with a negative sign up to -0.916 deg (Fig. 7) (excluding the SLS pinion). In the case of polymer gears, the distribution of deviations of the pressure angles of the both convex and concave sides of the teeth as to the sign is analogous. For gears, except those made in MEM technology (ABS material) and FFF (PET material), the deviations of the pressure angles, on both sides of the teeth, are positive (Fig. 11). For the MEM and FFF (PLA and PLA/PHA materials) the deviations of the gear tooth profiles are negative. The values of the tooth spiral angle for the concave and convex sides of the teeth obtained in the polymer models of pinions and gears were also evaluated. From the analysis of the graphs presented in Fig. 8 and Fig. 12, the following relationship can be observed: the deviation of the spiral angle on the concave side takes positive values for both the pinion and gear models (except for SLS models). Deviation values are comparable for both models. In the case of the convex side of the tooth of the pinion models, it is ambiguous. Positive values of spiral angle deviations were obtained for gears made with MEM technologies (ABS material), SLS (PLA material), FFF (PET material) (Fig. 12). The positive values of spiral angle deviations for the pinions were achieved for the SLS and DLP technology models (Fig. 8).

Based on DIN 3965 [18], the specialist measuring program for spiral bevel gears determined the parameters characterizing tooth geometry defined the gear accuracy class. The following parameters were taken into account: max. tooth spacing index error ($f_{p\max}$), max. tooth spacing error ($f_{u\max}$), tooth space total index error (F_p), calculated runout for each flank side and pitch line runout (F_r). The values of the received parameters defined the class of accuracy of individual gears. Hence polymer models of pinions made by PolyJet and DLP have obtained the 11th class of accuracy, pinions made by MEM (ABS material) and FFF (PET material) have obtained the 12th class of accuracy. The rest of models of pinions were beyond the accuracy class. Polymer gear models made by PolyJet, MEM (ABS material) and FFF (PET material) achieved the 11th class of accuracy, the rest of gear models were beyond the accuracy class.

In the literature it is difficult to find information on the accuracy of spiral bevel gears made with additive technologies. The only publication [19] presents comparable results, but only concerns PolyJet and MEM technologies.

CONCLUSIONS

To assess the accuracy of the polymer models of spiral bevel gears made by the incremental technologies, measurements were taken on a coordinate measuring machine using a specialized program dedicated to this type of gears. The parameters characterizing tooth geometry that affect the quality of gear work and the geometry of blanks were taken into account. Taking into consideration the parameter values obtained from the measurement, the gear accuracy classes were determined in accordance with DIN 3965. The highest 11th accuracy class was obtained by the pinions and the gears made in PolyJet technology. The gears made in MEM technology (ABS material) and FFF (PET material) were in the 11th accuracy class, while their pinions achieved the 12th accuracy class. The 11th accuracy class also obtained the pinion made by DLP technology. The gear in DLP technology has not been measured. Other models made [SLS, FFF (PLA and PLA/PHA materials)] were outside accuracy class.

In additive production methods, it is important to know the accuracy of mapping models in which there are surfaces with a complex shape (side surfaces of teeth of spiral bevel gear) whose geometry effects their functions. For each of the analyzed additive technologies, it was possible to identify the nature of errors in geometry of the teeth. This knowledge makes it possible to determine the geometry correction factors what allows to achieve a certain dimensional accuracy in the significant areas of the model.

Most publications dealing with the accuracy of additive technologies provide information on one additional technology (FDM) or synonymous technologies. The paper collects the results of the obtained accuracy for the same complex geometry model manufactured with the use of methods: PolyJet, MEM, FFF (for 3 materials), SLS and DLP.

The application of the philosophy based on the INDUSTRY 4.0 structure allowed developing a new approach to the process of geometric analysis of gears. The philosophy was based on a flow data model using network connections between structure elements. In this case, using parallel data in the cloud, it is possible to work in parallel in the system of manufacturing processes and measurement processes. In addition, selected users of system components may have continuous information on the accuracy of the prototype and, for example, they may make adjustments on the 3D-CAD model being the basis for the prototype additive method. Thus, the possibility of accelerating design, implementation and research works is achieved. It is also important to get information on the accuracy of the polymer gears manufactured incrementally. This allows you to make correction factors on the model in order to make the gears with increased accuracy relative to the original model.

REFERENCES

[1] Killi S.: "Additive Manufacturing. Design, Methods and Processes" (Ed. Killi S.), Pan Stanford Publishing Pte. Ltd., 2017, pp. 16–17.

[2] Srivatsan T.S., Manigandan K., Sudarshan T.S.: "Additive Manufacturing. Innovations, Advances, and Applications" (Eds. Srivatsan T.S., Sudarshan T.S.), CRC Press, 2016, pp. 25–26.

[3] Dziubek T.: *Polimery* **2018**, *63*, 49. http://dx.doi.org/10.14314/polimery.2018.1.8

[4] Rokicki P., Budzik G., Kubiak K. *et al.*: *Aircraft Engineering and Aerospace Technology: An International Journal* **2016**, *88* (*3*), 374. https://doi.org/10.1108/AEAT-01-2015-0018

[5] Krolczyk G., Raos P., Legutko S.: *Tehnički Vjesnik – Technical Gazette* **2014**, *21* (*1*), 217.

[6] Gajdoš I., Slota J.: *Tehnički Vjesnik – Technical Gazette* **2013**, *20* (*2*), 231.

[7] Batsch M., Markowski T., Legutko S. *et al.*: *Measurement* **2018**, *125*, 516. https://doi.org/10.1016/j.measurement.2018.04.095

[8] Dadley D.W.: "Handbook of Practical Gear Design", CRC Press LLC, 2002, p. 573.

[9] Pisula J., Płocica M.: *Acta Mechanica et Automatica* **2014**, *8* (*2*), 95.

[10] Oleksy M., Budzik G., Sanocka-Zajdel A. *et al.*: *Polimery* **2018**, *63*, 531. http://dx.doi.org/10.14314/polimery.2018.7.7

[11] Pisula J.: *Advances in Manufacturing Science and Technology* **2016**, *40* (*1*), 20. http://dx.doi.org/10.2478/amst-2016-0002

[12] Pisula J., Sobolewski B.: *Mechanik* **2014**, *2*, 128.

[13] https://www.klingelnberg.com/en/business-divisions/precision-measuring-centers/bevel-gear-software/ (access date 28.07.2018)

[14] https://www.klingelnberg.com/en/business-divisions/precision-measuring-centers/precision-measuring-centers/detail-page/product/p-40/ (access data 28.07.2018)

[15] Goch G.: *CIRP of Annals-Manufacturing Technology* **2003**, *52*, 662.

[16] "Bevel Gear. Fundamentals and Applications" (Ed. Klingelnberg J.), Springer-Verlag, Berlin Heidelberg, 2016, p. 20.

[17] Ratajczyk E.: "Coordinate measurement technique" The Warsaw University of Technology Publishing House, Warsaw 2005.

[18] DIN 3965 "Toleranzen fur Kegelradverzahnungen", Deutsche Norm, August 1986.

[19] Pisula J., Dziubek T., Przeszłowski Ł.: *Machine Dynamics Research* **2016**, *40* (*3*), 147. http://mdr.simr.pw.edu.pl/index.php/MDR/article/view/200/182

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