Geometrical accuracy of injection-molded composite gears

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Abstract: The geometrical accuracy of injection-molded gears made of PA6, PA66 and PPA filled with glass fiber (30, 35 and 50%) were investigated. Using the AMI software, the injection mold cavity and the injection point distribution were simulated and the orientation of the glass fibers in the product was determined. The low accuracy class of injection-molded gears may indicate the need to optimize the injection process, which will be the subject of further research.

Keywords: geometric accuracy, processing shrinkage, polymer gears, injection molding.

Dokładność geometryczna kompozytowych kół zębatych otrzymanych metodą wtryskiwania

Streszczenie: Zbadano dokładność geometryczną formowanych wtryskowo kół zębatych wykonanych z PA6, PA66 i PPA napełnionych włóknem szklanym (30, 35 i 50%). Za pomocą oprogramowania AMI przeprowadzono symulację gniazda formy wtryskowej i rozmieszczenia punktu wtrysku oraz określono orientację włókna szklanego w wyrobie. Niska klasa dokładności formowanych wtryskowo kół zębatych może wskazywać na konieczność optymalizacji procesu wtryskiwania, co będzie przedmiotem dalszych badań.

Słowa kluczowe: dokładność geometryczna, skurcz przetwórczy, polimerowe koła zębate, formowanie wtryskowe.

Currently, polymers are widely used in the engineering industry. Polymer gears have many advantages over their metal counterparts. They are characterized by many economic and utility advantages. Due to the combination of appropriately selected fillers, nanofillers or other modifiers, the mechanical and fatigue properties of almost every basic polymer can be changed [1, 2]. However, it should be remembered that the properties of polymeric materials are clearly different from those of metallic materials. Comparing these groups, it is easy to see that metals have a higher maximum service temperature, mechanical strength, and thermal and electrical conductivity. In turn, polymers have much better mechanical damping, thermal expansion, elongation at break and ductility. A significant advantage of polymer gears is the ability to work without external lubrication, lower production costs and the ability to suppress moderate shocks and impacts [3–6]. In the polymers processing industry, injection molding is one of the most popular technologies. The main advantages of this process is high precision and cost optimization in multi-series production. It has become a standard to perform CAE (Computer Aided Engineering) simulations before the injection mold design stage. This streamlines the design of the mold structure, and then obtaining the required part quality. It allows to determine the most optimal parameters of the manufactured products: injection pressure and time, temperature distribution in the product, places where the joining lines are formed, places susceptible to warping and sensitive to air bubbles, while saving time and money that would be needed to conduct these tests in real conditions [1, 2, 5].

However, it should be remembered that the results of computer modeling are a facilitation, not a final solution. Therefore, after completing the CAE simulation, the process should always be verified in real conditions, and for the obtained details, a geometric analysis should be performed in order to compare it to the model most accurately [7–9]. Ensuring high standards of control and quality processes is nowadays an indispensable requirement in a modern manufacturing company. Geometric accuracy of gears significantly affects the operation of the transmission, and more precisely the uniformity of the

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Table 1. Materials

Symbol	Polymer	Glass fiber, %	Trade name	Producer
P1	PA66/6T	50	Zytel PLS95G50DH2 BK261	DuPont
P2	PPA	35	Zytel HTN51G35HSL NC010	DuPont
P3	PA66/6T	35	Zytel PLS95G35DH1 BK549	DuPont
P4	PA66	–	Zytel 101L NC010	DuPont
P5	PA6	–	Tarnamid T-27 NATUR	Azoty Group
P6	PPA	30	Grivory HTV-3H1 BLACK 9205	EMS Chemie AG

motion transmission, which directly translates into the fatigue strength of the test system [9, 10]. Devices such as an optical scanner and coordinate measuring machines are widely used in the reverse engineering industry to ensure high quality products.

The paper presents an analysis of the geometric accuracy of gears made of glass fiber reinforced polymers (GF) obtained by the injection molding. Based on previous studies [11], reinforced polyamides (PA66, PA6) and polyphthalamides (PPA) were selected. After selecting the materials and establishing the basic data concerning the geometrical arrangement of the mold cavity, pilot injections were made and the obtained gears geometry was measured. The paper is a continuation of research on modified thermoplastic polymers used as elements of machines, including gears.

EXPERIMENTAL PART

Materials

The polymers used in the study and their symbols are listed in Table 1. Based on the tests of mechanical properties presented in the publication [11], compositions for the gear injection process were selected.

Methods

Geometric accuracy of gears was tested on the Atos III Triple Scan 16M optical scanner with the Atos Professional version 2018 software (Fig. 1). Before the measurement, the reference points were placed on the measured workpiece and directly next to it on the measuring Table. The Atos program and the MV 170 template dedicated to small details were used to perform the measurement.

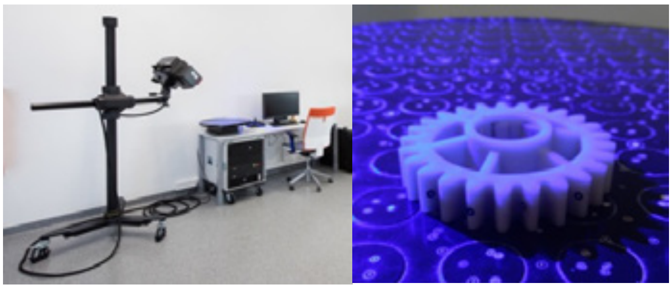


Fig. 1. Optical scanner Atos III Triple Scan 16M with a scanned gear placed on the measuring table

The tooth topography and the accuracy class of the gears were determined using a Klingelnberg P40 coordinate measuring machine and the Klingelnberg GINA program for cylindrical gears. The procedure of preparing and performing the measurement consisted in entering the wheel parameters into the GINA program, which made it possible to determine the base (reference) geometry of the wheels (KZ17 and KZ25). Then, the measuring pins were selected, the set of measurement parameters, the method of measuring the tooth topography, tooth profile tolerance, tooth line, tooth pitch, tooth radial runout and its thickness were determined. Three teeth spaced evenly around the circumference of the gear were selected to measure the outline and line. The pitch and thickness were measured for all teeth.

Injection molding initial numerical simulation

In order to optimize the geometry of two cylindrical gears with straight teeth, preliminary numerical simulations of polymer materials processing were performed in Autodesk Moldflow Insight version 2018 (AMI). The basic parameters of the gears used for the geometric accuracy tests are presented in Table 2. The designations KZ25 and KZ17 define the driven gear with the number of teeth equal to 25 (KZ25), similarly the designation KZ17 is the driving gear with the number of teeth 17.

Table 2. Gear wheels basic parameters

Parameter	Driven gear wheel KZ25	Driving gear wheel KZ17
Number of teeth	25	17
Pressure angle [°]	20	
Module [mm]	3	
Centre distance [mm]	63.292	
Face width [mm]	15	17
Outside diameter [mm]	81.584	56.990
Tooth thickness [mm]	4.717	4.712

The specialized AMI software enables the simulation of the mold cavity filling, the optimal distribution of the injection point, the determination of the glass fiber orien-

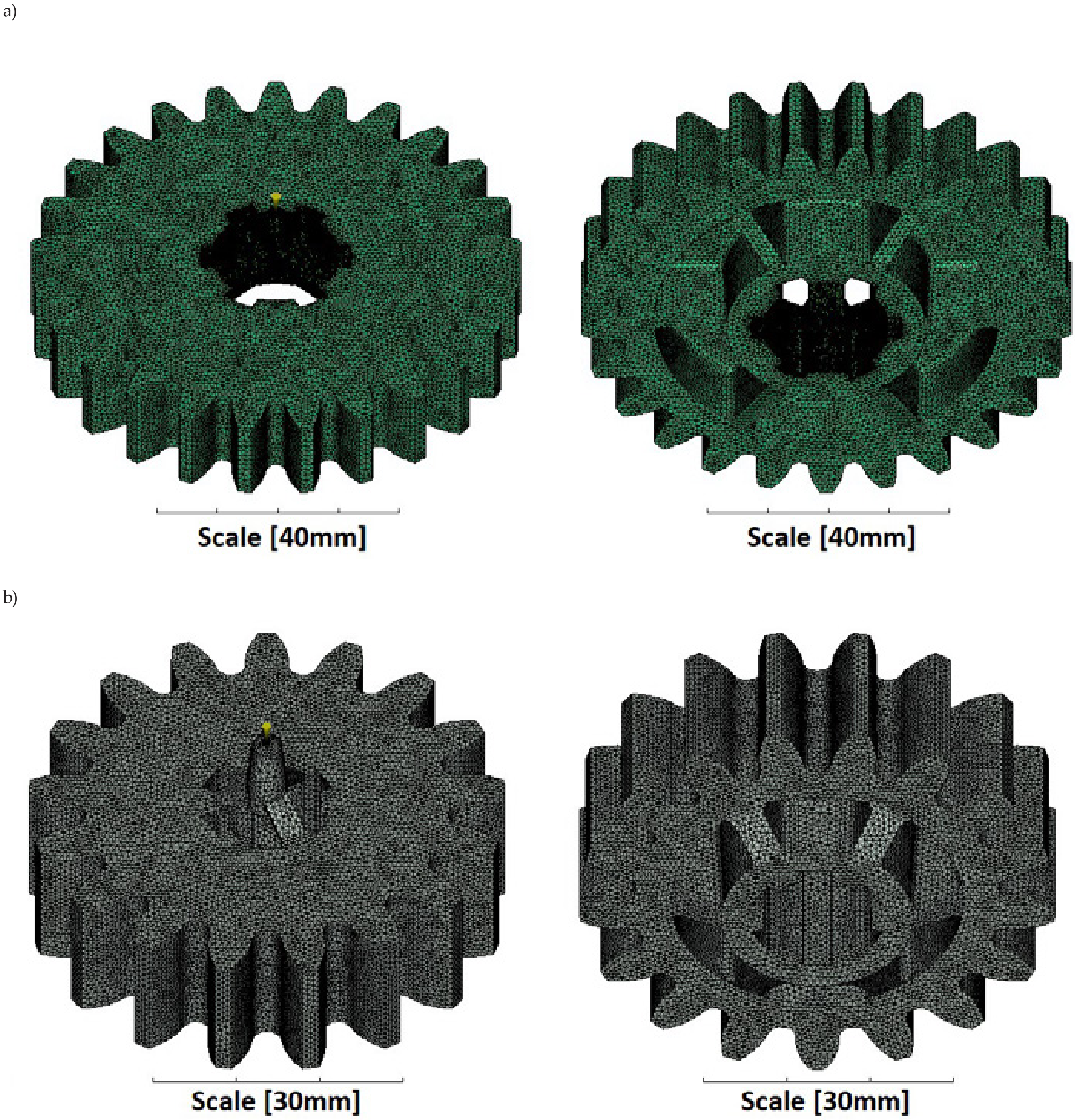


Fig. 2. Dual Domain mesh model for the gear wheel: a) KZ25, b) KZ17

tation in the product and the elimination or minimization of the connection lines number , air traps and places susceptible to warping. After importing to the program ready CAD models (Computer aided design) for KZ25 and KZ17, a parallel 3D Mesh tetrahedral finite element mesh and the injection point location were superimposed on them (Fig.2a, 2b). For KZ25 and KZ17, the tetrahedron edge for approx. 0.5 mm and the finite element equilateral coefficient was approx. 1.51. The total number of triangles forming tetrahedral for KZ25 was 81078 and for KZ17 - 52540.

In order to carry out endurance tests for hybrid polymer gears that could be used in the automotive industry, a prototype injection mold was made. The research project involves injection of gears from various polymers. A material called Zytel HTN92G45DH2 BK083 was selected for further numerical analysis of AMI. An analysis of the injection mold cavity filling process was simula-

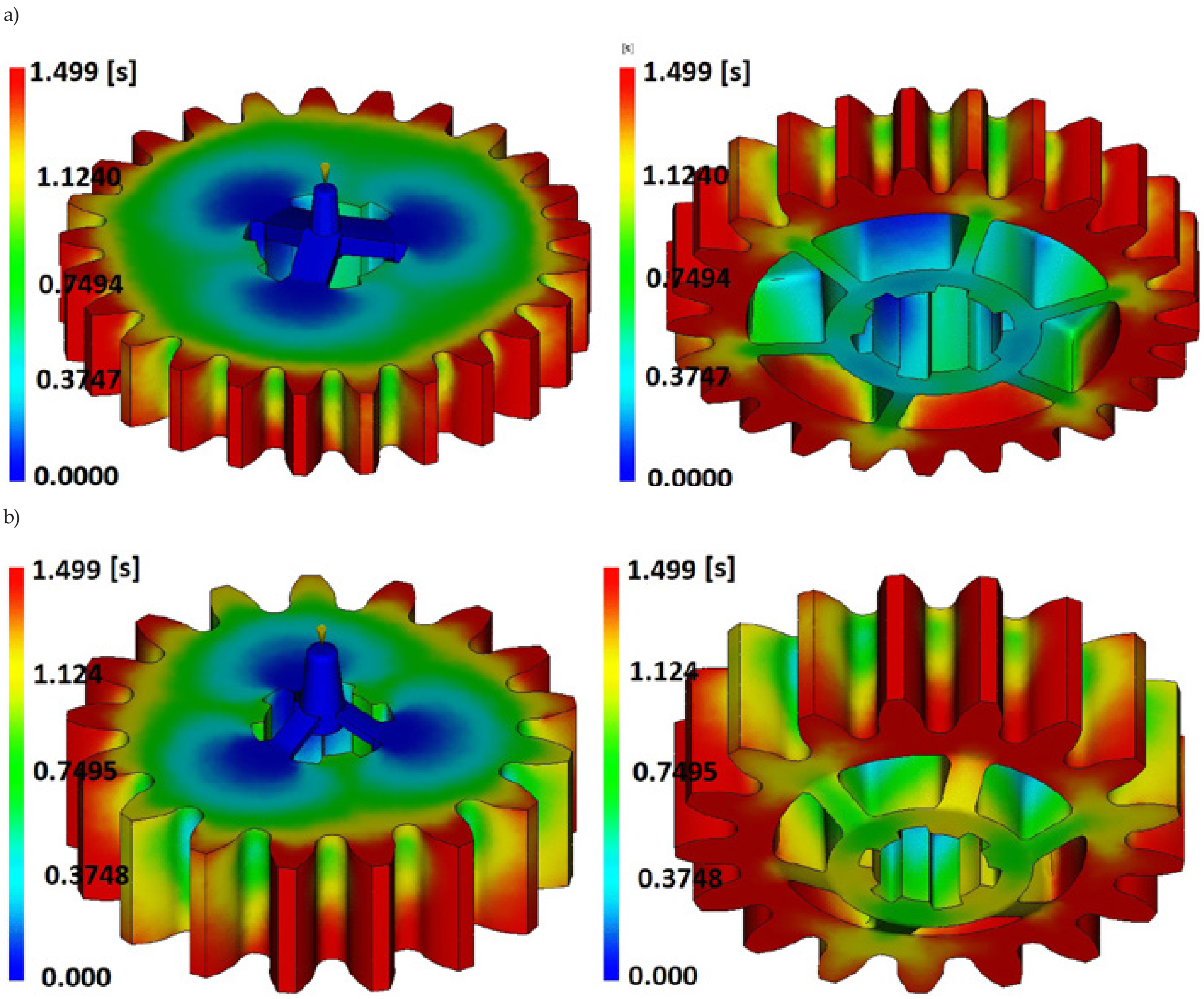


Fig. 3. Time to fill the mold cavity for the gear wheel: a) KZ25, b) KZ17

ted (Fig. 3a, 3b). Based on the results obtained for both versions of the KZ25 and KZ17 gears, it can be concluded that the stream velocity is influenced by the shape of the molding and the geometry of the pouring channel. The analysis below presents the image of the mold cavity filling at the moment of switching the injection phase into the pressing phase.

In the further part of the analysis, the location of the joining line in the product was determined, as shown in Figs. 4a and 4b. The connection lines are the undesirable effect of the two polymer streams contact flowing from opposite directions. The smallest defects in the product arise when the fronts of these streams come into contact with each other under the influence of high pressure, while the melt temperature is still high. Joining lines have a negative impact on the mechanical and aesthetic properties of the products.

The AMI software allowed the simultaneous determination of the deformation places in both gears (Figs. 5a, 5b). The deformations due to contractions, in the direction of the wall thickness and in the parting plane, occur in rounded and bent parts, *e.g.* at the tips of the teeth.

Table 3. Drying and injection molding parameters

Polymer	P1	P2	P3	P4	P5	P6
Drying time [h]	2–4	2–4	2–4	2–4	2–6	2–8
Drying temperature[°C]	80	80	80	80	80	100
Permissible humidity [%]	0,1	0,2	0,2	0,2	0,12	0,1
Injection molding temperature [°C]	230–270	280–300	280–290	285–305	280–300	320–330
Mold temperature [°C]	60–80	50–90	70–120	70–120	80–120	140–180

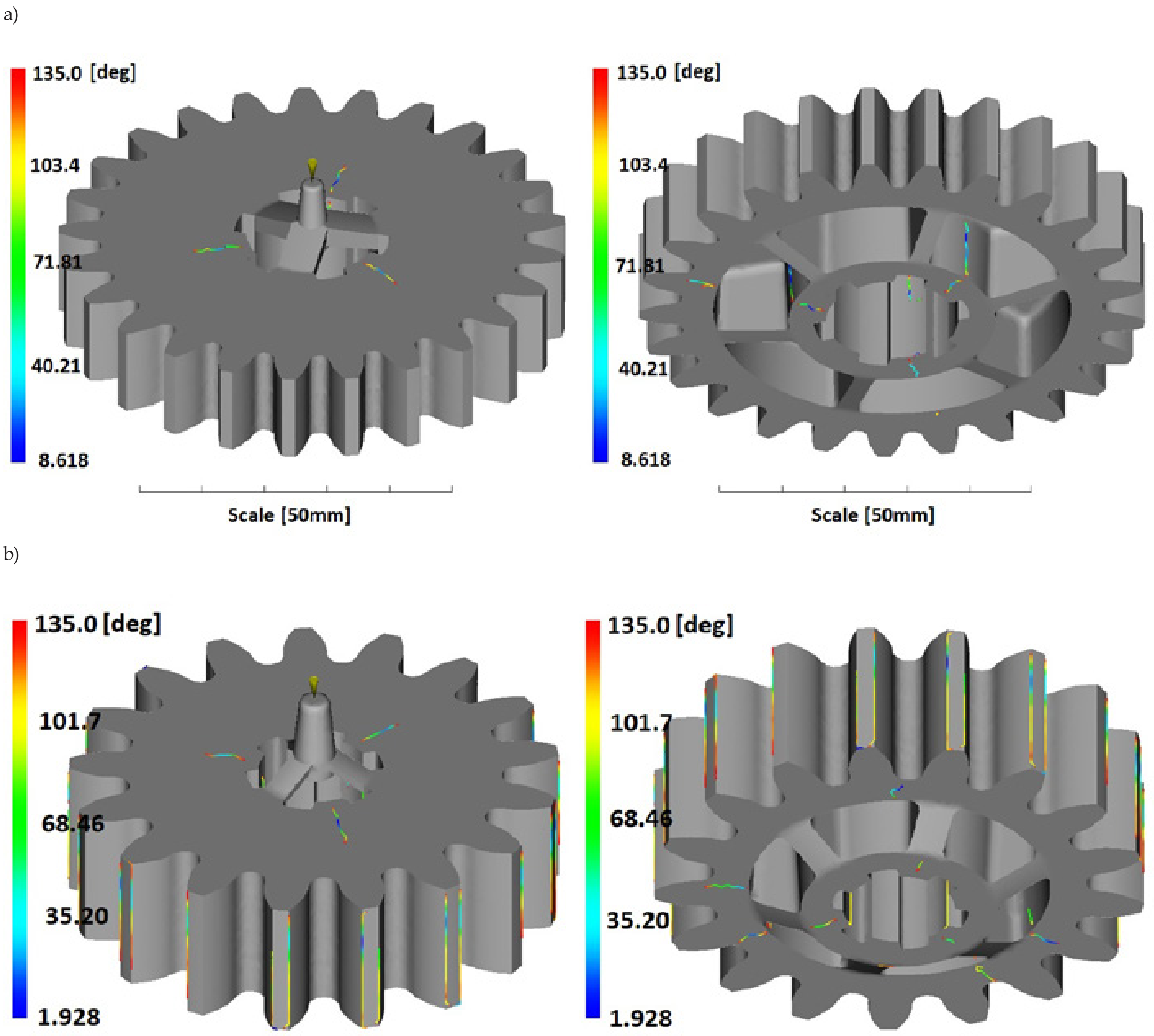


Fig. 4. Arrangement of the connection line for gear wheel: a) KZ25, b) KZ17

It was possible to improve the geometry of the KZ25 and KZ17 inlet channel, which allowed to avoid uneven filling of the injection mold cavities. The results of the simulation, to a large extent eliminated the deformation caused by the differences in the value of the material shrinkage in the direction of the wall thickness and the plane of the partition cross-section. It has been found that the length of the injection time has a direct impact on subsequent warping, and increasing the pressing time will minimize dips on the final products.

Injection molding

The gear wheels were obtained by injection molding using an ENGEL EVC 310/80 injection molding machine and an injection mold specially designed for this purpose, shown in Fig. 6.

Before the injection process, the polymers were dried in accordance with the parameters listed in Table 3. The moisture content was checked immediately before injection with a hygrometer. It should be mentioned that the moisture content has a significant influence on the defects of the moldings, i.e. the reduction of mechanical strength and visible decompression, resulting from the residual moisture in the polymer [12]. Table 3 shows the drying parameters as well as injection and mold temperatures.

The selected P1-P6 polymers were used for the injection molding of gears in two sizes: KZ17 and KZ25. 40 of each variant were made for testing, giving total number of 480 gear wheels. Fig. 7a and 7b show exemplary details. Each of the gears was weighed and visually checked for defects such as burns, traces of flow and flashes. Samples that did not meet the quality requirements and could distort the test results (Figs. 8a, 8b) were eliminated.

In the case of the defects presented in Fig. 8, further injection tests were carried out by modifying the setting parameters. The burns on the joining lines and tooth tips

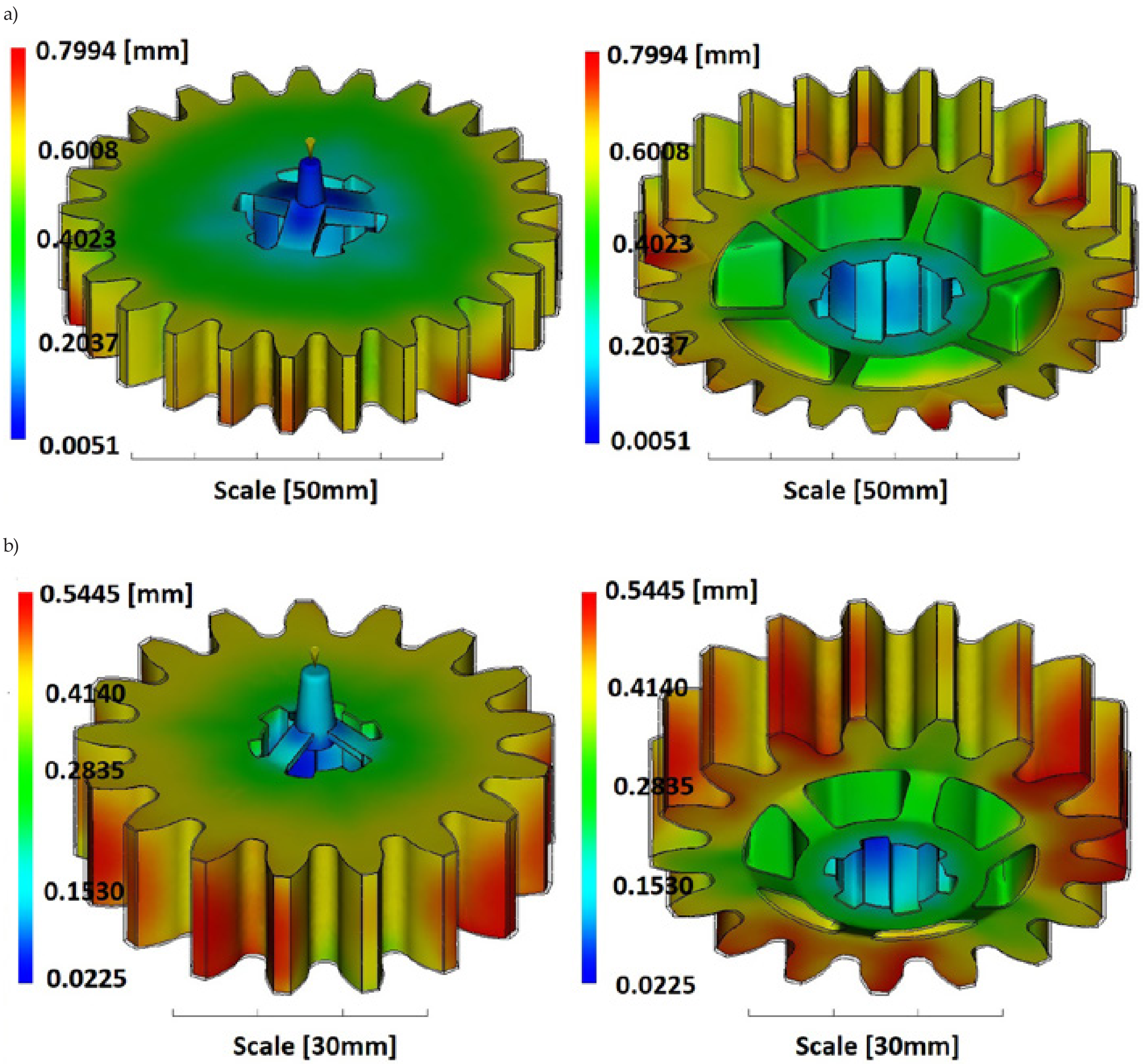


Fig. 5. Distribution of deformations in gear wheel: a)KZ25, b) KZ17

Table. 4. The gears KZ25 accuracy class (DIN 3962)

Gear	Tooth profile		Tooth trace		Pitch		Thickness and runout F_r, R_s	Gear class
	Left	Right	Left	Right	Left	Right		
P1	>>	12	>>	11	12	12	12	>>
P2	12	12	10	11	12	12	12	12
P3	>>	12	12	>>	12	12	12	>>
P4	>>	>>	>>	>>	12	12	12	>>
P5	>>	>>	>>	>>	12	12	12	>>
P6	12	11	11	11	12	12	12	12

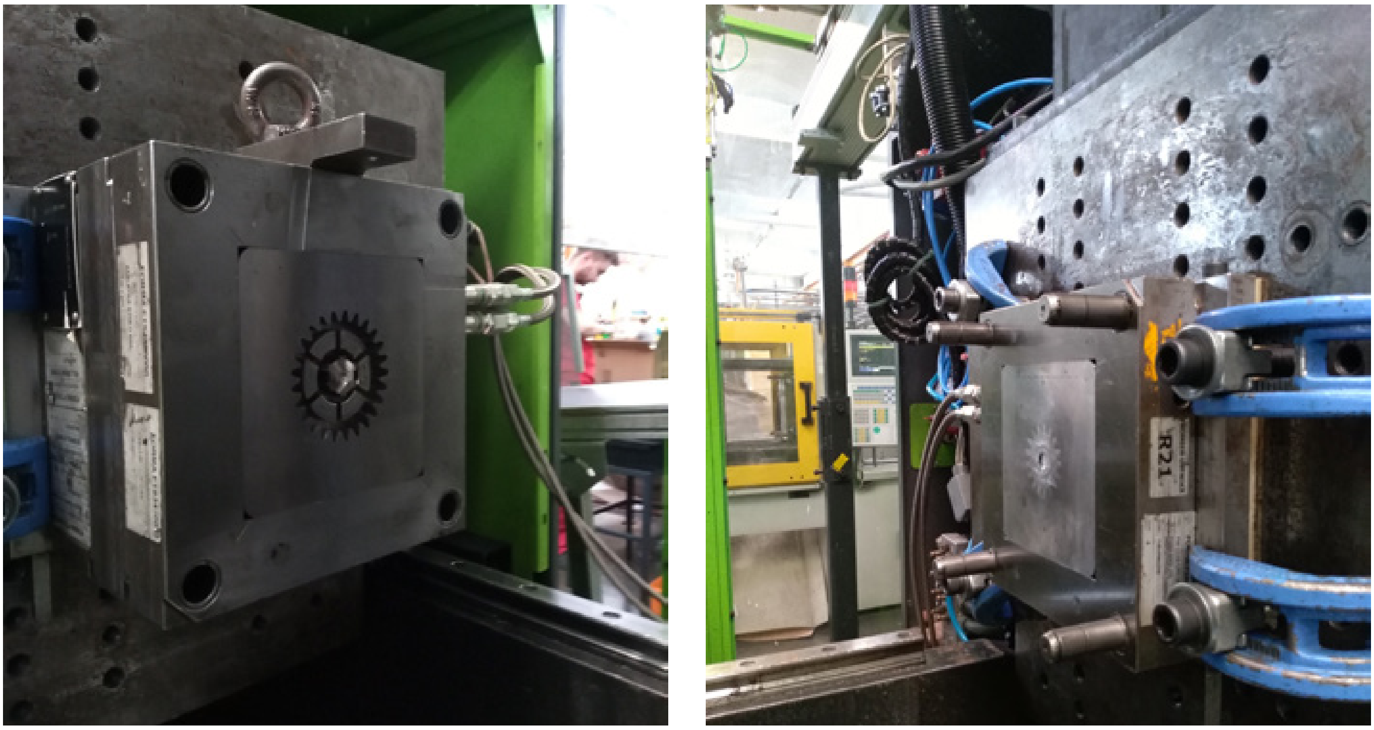


Fig. 6. Injection mold seat for the KZ25 gear wheel

Fig. 7. Gear wheel with gating system: a) KZ25 (P6), b) KZ17 (P4)

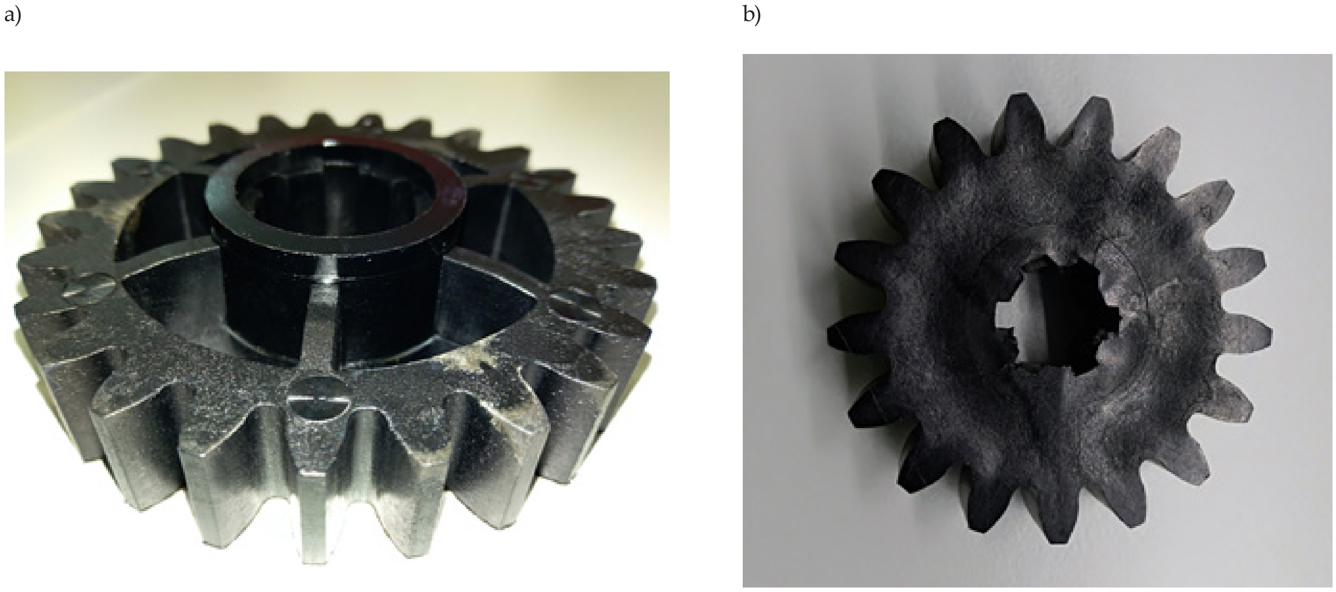


Fig. 8. Defects of KZ25 (P6) moldings: a) burns on the connection lines and tooth tips, b) collapsed

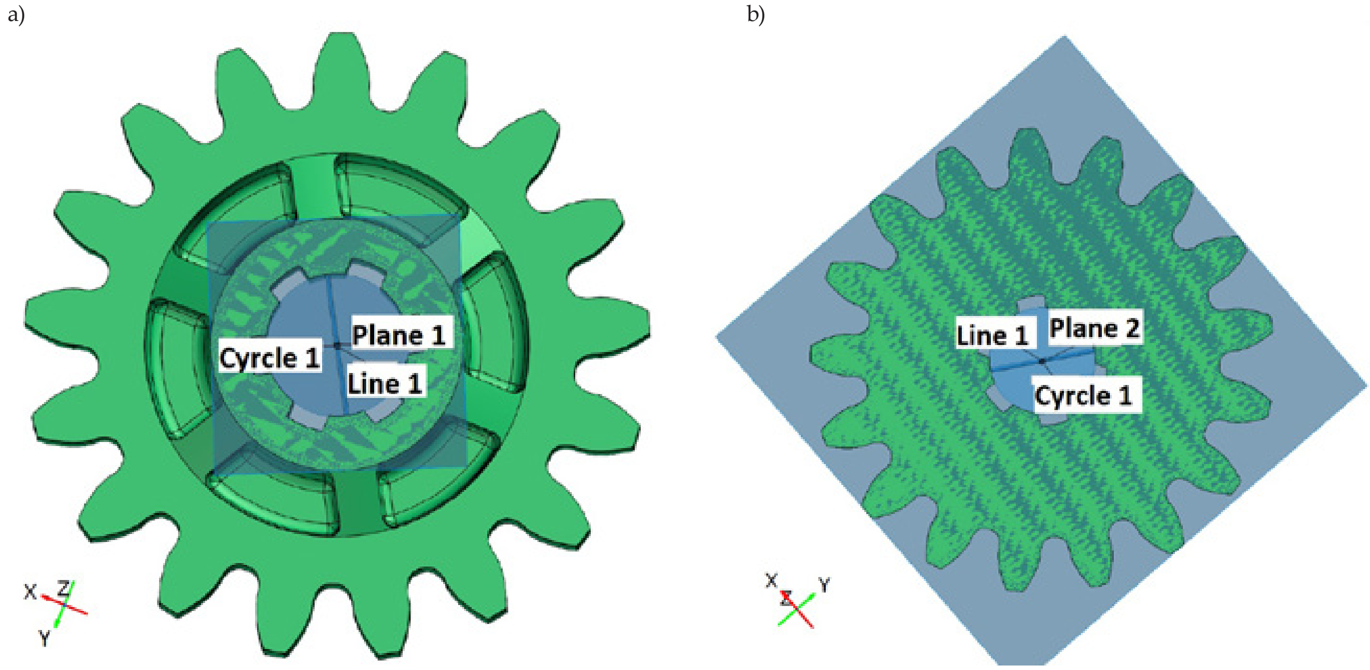


Fig. 9. Homing the plane of the measured detail KZ17 (P2) with respect to the 3D model

were eliminated by the reduction of the injection speed in its last stage and the implementation of design changes by adding additional vents in the injection mold seat (Fig. 8a). The injection moldings collapsed were corrected by increasing the clamping force and extending the clamping time. Finally, on the basis of datasheets and own experience, the optimal injection conditions for each of the P1-P6 polymers were determined.

Geometric accuracy

The actual gear cross-section was compared with the 3D model by superimposing the injection gear geometry made of P2 polymer and the 3D model. Two baselines of plane and wheels were made as shown in Fig. 9. For all types of polymers used, in the case of the KZ25 gear wheel, a significant difference was found near the body hub in relation to the 3D model. It was eliminated by replacing the sleeve ejector (Fig. 10).

Other modifications to the injection mold that were implemented after the photos were taken with the optical scanner are:

– hollowing the ribs (eliminating the bend) – matching the ingot (inlet flashes, loosening the product with additional vents)

– increasing the number of smaller ejectors on the joining lines, between the ribs due to burns (replace with fi = 4 mm)

– increasing pressure and extending the pressing time during the cycle, which will reduce dips on the product.

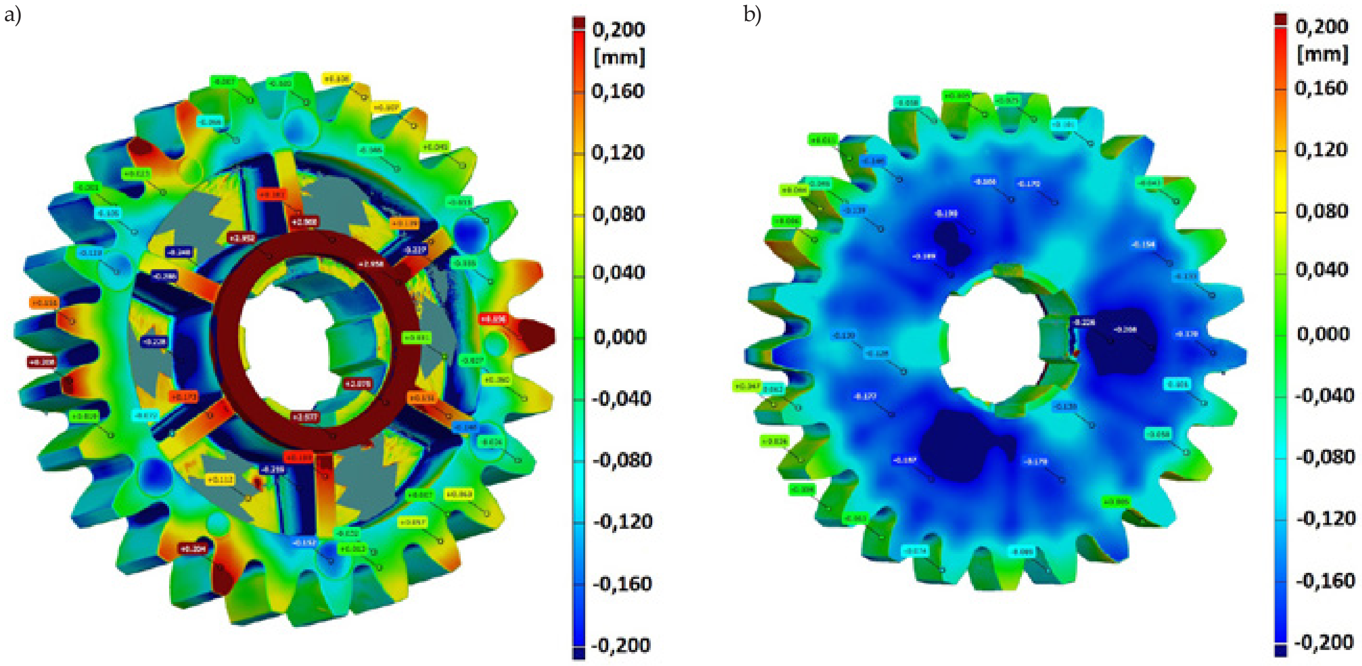


Fig. 9. Homing the plane of the measured detail KZ17 (P2) with respect to the 3D model

Geometric accuracy using the P40 coordinate measuring machine

The Klingelnberg GINA program was used to measure cylindrical gears geometric accuracy. The results s include data on:

– outline deviations ($F_{H\alpha}$ – total profile deviation; $f_{f\alpha}$ – profile form deviation $f_{f\alpha}$, C_{α} – profile crowning, $f_{H\alpha}$ – profile slope deviation, f_{Ko} – vertex modification),

– deviations of the tooth line lateral outline (F_{β} – total tooth trace deviation, $f_{f\beta}$ – tooth trace form deviation, $f_{H\beta}$ – tooth trace slope deviation, C_{β} – lead crowning C_{β}),

– scale deviations (f_p – single scale deviations, F_p – total cumulative pitch deviation, f_{pmax} – max. single pitch deviation, f_{umax} – max. tooth spacing (pitch) error, R_p – graduation fluctuations, $F_{pz/8}$ – cumulative pitch-span deviation for eight teeth),

– runout error (F_r),

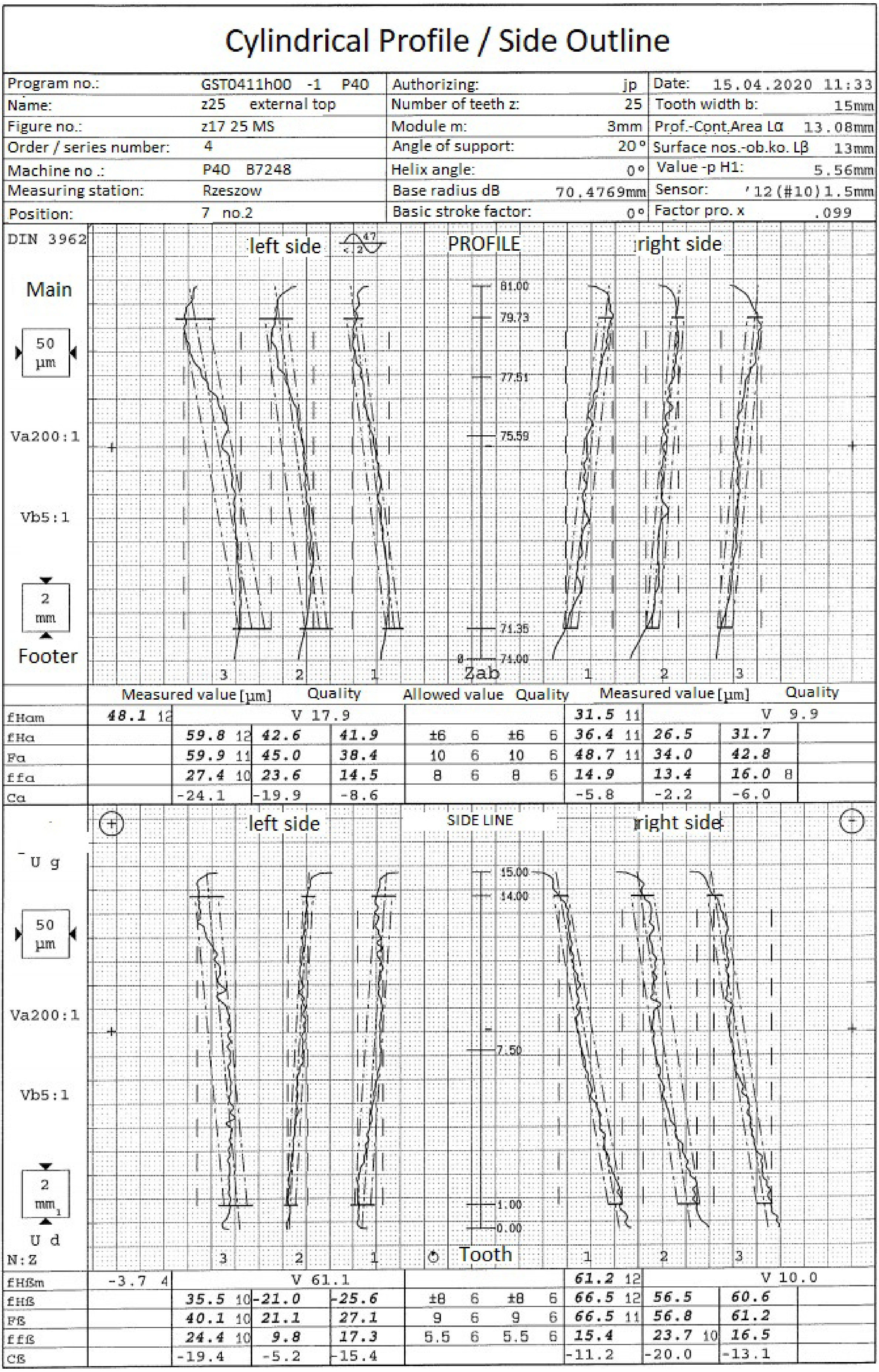
– tooth thickness variation (R_s) and (vi) tooth topography.

Measurements of the wheels obtained as part of the injection process tests were used to determine the geometric accuracy of the wheels and on their basis, the seats of the injection molds and the parameters of the injection process were improved. Subsequent measurements of the gears were performed in order to check the stability (repeatability) of the injection process and to determine the geometric accuracy of the gears intended for later strength tests of the gears.

The polymer gears measurement results were obtained in the form of reports. An exemplary measurement report for the KZ25 large wheel made of P2 material is shown in Figs. 11–13. On the basis of the results for all wheels, the accuracy class of the individual gear was determined. Table 3 shows the results of the accuracy classes for the KZ25 gear wheels.

The gear accuracy class is influenced by the accuracy classes of the gears geometry components, such as the tooth contour, line, pitch and thickness. The least accurate toothing parameter determines the gear accuracy class. The results showed that the highest accuracy class was achieved by the KZ25 wheels made of P2 and P6 polymers (Table 3), whose tooth lines had the 11th accuracy class and the 12th accuracy class was influenced by higher values of the parameters of the tooth profile and pitch. The other KZ25 gears were outside the accuracy class 12. It should be emphasized that the KZ25 gear wheels made of P4 and P5 materials obtained the values of the profile and tooth line parameters for both sides of the tooth outside the 12^{th} accuracy class.

The topography of the teeth of the research circles was assessed, which was determined on the basis of the measurement of 9 contours evenly distributed on the appropriate section of the contour evaluation (L_{α} segment defined according to the standard) and 7 tooth lines located on the appropriate section of the tooth line evaluation (L_{α} segment defined according to the standard). The topography of gear tooth made of P2 is shown in Fig. 12. Each set of measured wheels made of a specific material was characterized by a specific geometry of the topography. Most often, the topography showed deviations of the tooth profile (P2, P4 and P5), but for the P2 material the profile angle decreased slightly, while for the other materials (P4 and P5), the profile angle increased significantly. There were slight concavities in the topographies of the teeth of all the wheels. The P5 wheel had a distinct concavity on the right flank (approx. 50 μm). For the remaining materials, there were no other distinctive geometry changes on the flanks of the teeth.



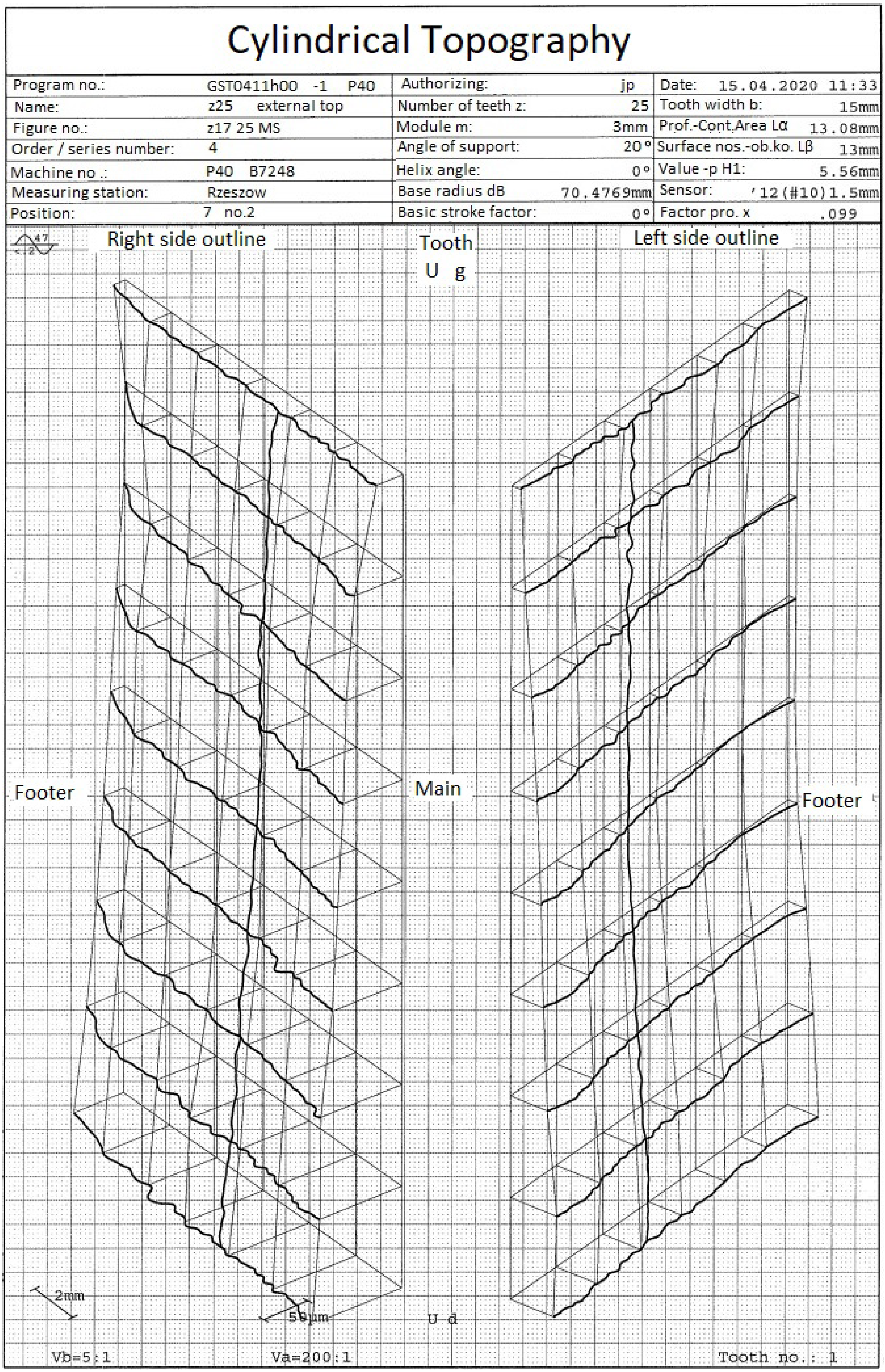
Cylindrical Profile / Side Outline

Program no.:	GST0411h00 -1 P40	Authorizing:	jp	Date:	15.04.2020 11:33
Name:	z25 external top	Number of teeth z:	25	Tooth width b:	15mm
Figure no.:	z17 25 MS	Module m:	3mm	Prof.-Cont.Area Lα	13.08mm
Order / series number:	4	Angle of support:	20 °	Surface nos.-ob.ko. Lβ	13mm
Machine no .:	P40 B7248	Helix angle:	0 °	Value -p H1:	5.56mm
Measuring station:	Rzeszow	Base radius dB	70.4769mm	Sensor:	'12 (#10) 1.5mm
Position:	7 no.2	Basic stroke factor:	0 °	Factor pro. x	.099

	Measured value [µm]		Quality		Allowed value	Quality			Measured value [µm]		Quality	
fHαm	48.1 12	V 17.9							31.5 11	V 9.9		
fHα		59.8 12	42.6	41.9	±6	6	±6	6	36.4 11	26.5	31.7	
Fα		59.9 11	45.0	38.4	10	6	10	6	48.7 11	34.0	42.8	
ffα		27.4 10	23.6	14.5	8	6	8	6	14.9	13.4	16.0 8	
Cα		-24.1	-19.9	-8.6					-5.8	-2.2	-6.0	

fHβm	-3.7 4	V 61.1							61.2 12	V 10.0		
fHβ		35.5 10	-21.0	-25.6	±8	6	±8	6	66.5 12	56.5	60.6	
Fβ		40.1 10	21.1	27.1	9	6	9	6	66.5 11	56.8	61.2	
ffβ		24.4 10	9.8	17.3	5.5	6	5.5	6	15.4	23.7 10	16.5	
Cβ		-19.4	-5.2	-15.4					-11.2	-20.0	-13.1	

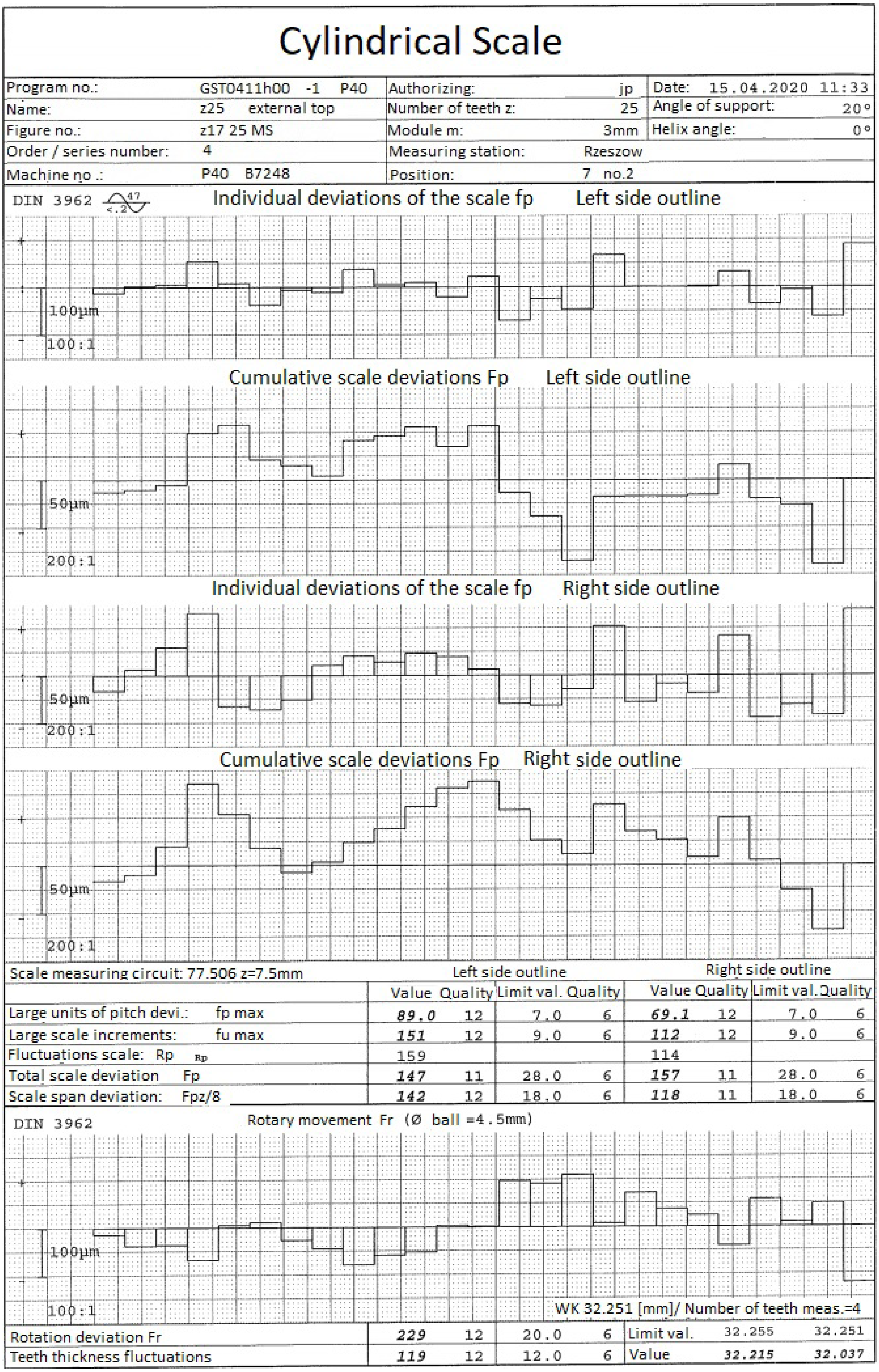
Fig. 11. Profile and tooth line of a large gear wheel made of P2 material (KZ25)



Cylindrical Topography

Program no.:	GST0411h00 -1 P40	Authorizing:	jp	Date:	15.04.2020 11:33
Name:	z25 external top	Number of teeth z:	25	Tooth width b:	15mm
Figure no.:	z17 25 MS	Module m:	3mm	Prof.-Cont.Area Lα	13.08mm
Order / series number:	4	Angle of support:	20°	Surface nos.-ob.ko. Lβ	13mm
Machine no.:	P40 B7248	Helix angle:	0°	Value -p H1:	5.56mm
Measuring station:	Rzeszow	Base radius dB	70.4769mm	Sensor:	'12(#10)1.5mm
Position:	7 no.2	Basic stroke factor:	0°	Factor pro. x	.099

Fig. 12. Topography of a large gear tooth made of P2 material (KZ25)



Cylindrical Scale

Program no.:	GST0411h00 -1 P40	Authorizing:	jp	Date:	15.04.2020 11:33
Name:	z25 external top	Number of teeth z:	25	Angle of support:	20°
Figure no.:	z17 25 MS	Module m:	3mm	Helix angle:	0°
Order / series number:	4	Measuring station:	Rzeszow		
Machine no.:	P40 B7248	Position:	7 no.2		

DIN 3962 Individual deviations of the scale fp Left side outline

Cumulative scale deviations Fp Left side outline

Individual deviations of the scale fp Right side outline

Cumulative scale deviations Fp Right side outline

Scale measuring circuit: 77.506 z=7.5mm

		Left side outline				Right side outline			
		Value	Quality	Limit val.	Quality	Value	Quality	Limit val.	Quality
Large units of pitch devi.:	fp max	89.0	12	7.0	6	69.1	12	7.0	6
Large scale increments:	fu max	151	12	9.0	6	112	12	9.0	6
Fluctuations scale: Rp	Rp	159				114			
Total scale deviation	Fp	147	11	28.0	6	157	11	28.0	6
Scale span deviation:	Fpz/8	142	12	18.0	6	118	11	18.0	6

DIN 3962 Rotary movement Fr (Ø ball =4.5mm)

WK 32.251 [mm]/ Number of teeth meas.=4

Rotation deviation Fr	229	12	20.0	6	Limit val.	32.255	32.251
Teeth thickness fluctuations	119	12	12.0	6	Value	32.215	32.037

Fig. 13. Tooth pitch and thickness of a large gear wheel (KZ25) made of P2 material

The analysis of parameters concerning: wheel pitch, radial runout and tooth thickness ranked the wheels in accuracy class 12. The graph presented in Fig. 14 shows the average value of the total deviations of the pitches for the KZ25 wheels for both the right and the left side of the tooth. The fluctuations in the total pitch deviations are the smallest for wheels made of P4 and are about 100 μm, then there are P5 wheels which reach about 150 μm. The highest value of F_p was achieved by wheels made of P3 material. The tooth thickness values for all wheels are less than the nominal thickness.

The results for the KZ17 gear wheels are discussed in detail in the reference [9]. It should be emphasized, however, that despite the lowest values of measured parameters obtained by small wheels made of P3, the results of all KZ17 gear wheels were still outside the 12th accuracy class.

CONCLUSIONS

Using the AMI software, simulations of the nest and the distribution of the injection point were carried out, and the orientation of the glass fibers in the product was determined. As a result, the number of joining lines, air traps and warping spots have been reduced. Based on the simulation, it was found that the stream velocity and the geometry of the inlet channel have an impact on the shape of the injected gears. Too low injection speed results in the formation of a joint line, reducing the moldings strength. The tops of the teeth were determined to be the most vulnerable places. To prevent warping of moldings, it was decided to introduce a longer hold down time. The information obtained is extremely important in the workshop practice of gears injection molding, because they have a direct impact on the quality and accuracy of the manufactured parts. Optical scanner measurements revealed the differences between the products made and the 3D model. Thanks to this, it was possible to correct the injection mold, which eliminated most of the detected inaccuracies. The best results were obtained for the gear wheel made of P4 polymer (PA66 without glass fiber). The significantly worse results for other tested wheels can be explained by differences in transverse and longitudinal shrinkage, which depend on polymer type and filler content used. The low accuracy class of injection-molded gears may indicate the need to optimize the injection process, which will be the subject of further research.

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