The paper presents a geometrical modeling of roughing operation of a combustion engine’s crankshaft pins using internal rotary milling method, i.e. with use of a milling head having its cutting inserts inwardly directed. For this purpose a geometrical model of such machining operation has been developed, i.e. the crankshaft and the milling head were modeled in CAD system. The model of crankshaft-milling head system featured predefined suitable geometrical constraints and determined mutual mobility of the both elements. Shape of the crankpin after rotary milling, and thus as a consequence, accuracy of the machining operation, were determined in result of performed simulation of this machining operation.

**Key words**: CAD modeling, rotary milling, crankshaft, internal milling head

1. INTRODUCTION

The crankshaft belongs to one of the most responsible structural components of combustion engine, taking part in conversion of reciprocating motion of the piston into rotary motion of the crankshaft [10]. Design of the crankshafts and narrow tolerances related to deviations in shape, position and dimension set high qualitative requirements before their manufacturing processes. Structure of the manufacturing process depends on volume of production and overall dimensions of the crankshafts, as well as shape of blanks. Actually, in series production within domestic industry, internal rotary milling or planetary milling is generally implemented as roughing operation with use of milling head having its cutting inserts inwardly directed [2, 3, 5]. Profiling and finishing operations of the crankpins take place in two separate operations by grinding. Generally, in mass production the crankpins of crankshafts are roughing by planetary milling, while shape machining – by rotating milling with internal milling head. The main objective of the roughing operation is to ensure large depth of the cutting, and the same high efficiency. The purpose of
this article is to determine shape of the crankshaft pin after rough rotary milling with the internal milling head using the geometric model. The results presented in this paper belong to continuation of the research work concerning modeling of rough rotary milling of crankshafts pins with the internal milling head. In the publication [7] a modeling method is presented, with the use of an analytical model, of the rough milling operation of the crankshaft pins from diesel engine with 6 double cranks.

2. METHOD OF GEOMETRICAL MODELING

Machining cycle of a single crankpin consists of three phases:
- approach with linear motion of the rotating milling head to immovable crankshaft pin, and penetration of the milling head into desired depth of the crankpin, (starting position);
- proper machining cycle consisting of one full rotation of the crankshaft;
- retracting with linear motion of the milling head from the crankpin and positioning to machining of the next crankpin.

Modeling of the machining process was limited to the second phase, when surface of the crankpin is shaped. For this purpose, basing on the design documentation, parametrical model of the crankshaft with 6 double cranks from diesel engine and parametrical model of the ring-shaped internal milling head (on the basis of Heller Co. materials) were modeled in the 3D module of the Inventor CAD system (Figure 1).

The milling head consists of repeating segments, each from them comprises three different cassettes equipped with cutting inserts. In general, the cutting inserts from each cassette perform machining of a different segment of crankpin’s surface along its length (in longitudinal section) [5]. For example, the Figure 2 shows a view of a single segment comprising 3 different cassettes.

In general, geometric modeling based on 3D modeling modules of CAD systems uses Boolean operations performed on the models of the objects being subject of the analysis [8, 9]. Models generated this way can be used, for example, for assessment of geometrical accuracy of the machining, to modeling of machining traces, or could be the basis to further analysis.

In the presented work a different solution was used. The assembly of the milling head and the machined crankpin were parametrically modeled in 3D module of the CAD system. Next, by defining a suitable geometrical constraints, mutual mobility of both elements above mentioned has been specified, i.e.:
- rotary motion of the milling head with constant speed;
- rotary motion of the machined crankshaft with constant speed;
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- linear displacement of the center of the milling head to maintain tangency of internal equivalent cylindrical surface of the milling head to theoretical external cylindrical surface of the machined crankpin.

Figure 1. Scheme of machining operation of the crankshaft pin with internal milling head: 1 – the crankshaft with 6 double cranks; 2 – the internal ring-shaped milling head; 3 – the crankpin [7]

Figure 2. View of a single segment of the milling head; 1 – D21-1023.00VA582 cutting insert; 2 – D21-1024.00VA582 cutting insert; 3 – D21.997-01VA582 cutting insert; 4 – cassettes constituting a single segment; $l_0$ – points for which the path of motion was generated in the model [7]
To maintain full representation of kinematics of the machine tool, additional geometrical constraints have been defined – i.e. displacement of rotation axis of the milling head in plane of its motion. Additionally, for representation of the real machining conditions, the following have been adopted: a limitation of the simulation time due to specified rotational speed of the machined crankshaft and requirement of one full rotation of the machined crankshaft.

Next, with help of tracking function, in selected cross-sections of the milling head which intersect edges of the cutting inserts of a single segment of the milling head in \( l \) points, the path of these points has been specified. This path consists of 2400 points (such value results from the simulation time and limitations of the CAD system) connected to each other by spline type curve (Figure 3) (in case of the analytical method presented in work [7], coordinates of 10915 points, which have been connected by polyline, were calculated).

In the next step of the proceeding, spline type curves obtained in the geometric method for particular cross-sections of the milling head were exported in the native format, while further analysis of the curves was performed in 2D modeling module of the CAD (AutoCAD) system. In this module, based on the spline curves obtained for 21 cross-sections of the milling head, using the boundary function to create the envelope, corresponding contour of the cross-section of the machined crankpin has been generated. In the successive steps, based on the
generated contours of the cross-sections of the machined crankpin, a solid model of the crankpin after the machining was created. For this purpose, the loft function of the Inventor system was used.

3. TESTING AND ANALYSIS OF THE RESULTS

Machining operation of selected crankpins of the crankshaft with 6 double cranks of Mercedes trucks diesel engine was analyzed [6] in the paper. As the blank for the crankshaft, a die forging from 38MnVS SBY steel of dimensions: diameter of the main journals $\varnothing 109^{7.7}$ mm, diameter of the crankpins $\varnothing 96^{2.7}$ mm, and overall length of the forging – 1106 mm was used. Axes of the crankpins: 1&6, 2&5, and 3&4 are arranged on diameter of $\varnothing 155$ mm every $120^\circ \pm 1^\circ 30'$ After finishing the machining with grinding, tolerance of angular position of the crankpins amounts to $\pm 0.17^\circ$ (i.e. $\pm 10.2'$). Manufacturing process of the crankshaft with 6 cranks comprises the following basic operations: milling of faces and machining of center holes, turning of the main journals, rotary milling of the crankpins with internal milling head to diameter of $\varnothing 91.5^{0.01}$ mm, drilling of oil passages, semi-finish grinding of the main journals, semi-finish grinding of the crankpins to diameter of $\varnothing 90.5^{0.07}$, finish grinding of the main journals, finish grinding of the crankpins to $\varnothing 90^{0.014}$ mm, dynamic balancing and oscillating superfinishing of the main journals and the crankpins. Geometry of the machined crankpins is determined by the radius $r_{cp} = 45.75^{0.15}$ mm and the crank throw $r_c = 77.5^{0.1}$ mm. Equivalent cylindrical surface of the milling head has the radius of $r_{mc} = 210$ mm. The milling head of the KF 420/43a type made by Boehlerit Co. features $l_n = 12$ segments on its circumference, while each of the segments consists of 3 cassettes marked as: D31-540, D31-541, D31-543. Total number of the cutting inserts in these 3 cassettes amounts to 10. Denomination of particular inserts and their geometry in the working system are as follows: D21-1023.00VA582 – $\gamma_{se} = 8^\circ$, $\alpha_{me} = 5^\circ$, $\gamma_{me} = -5^\circ$; D21-1024.00VA582 – $\gamma_{se} = 3^\circ$, $\alpha_{me} = 5^\circ$, $\gamma_{me} = -5^\circ$, while the insert marked as D21.997-01VA582 participates in machining of part of lateral surfaces of the crank only. The following parameters have been used in the analysis: width of the milling head that machines the crankpin on the length of $B = 40$ mm, and its division into $k = 21$ planes (cross-sections of the milling head) perpendicular to axis of the crankpins, evenly spaced every 2 mm. As result of the assumed division were obtained $l_{p} = 32$ points on edges of the cutting inserts, which are presented in the Figure 2 in form of dots.

In industrial practice it is noticed that optimal cutting speed in case of rotary milling of the crankpins of the crankshaft having 6 double cranks, produced from 38MnVS SBY steel, amounts to about 100 m/min. Based on this, rotational
speed of the milling head has been calculated, assumed as constant value of \( n_{mc} = 75.8 \text{ rpm} \). On the basis of the research carried out within framework of the study presented in [7], rotational speed of the machined crankshaft was assumed as equal to \( n_{cs} = 2.5 \text{ rpm} \). Penetration of the milling head into the crankpin occurs with immovable crankshaft for \( \psi(t = 0) = 0^\circ \) and \( \alpha_0(t = 0) = 0^\circ \) – Figure 2 [7], i.e. in such position of the crankpin axis for which both axis of this crankpin, axis of the main journals, and rotation axis of the milling head are positioned in one plane. During penetration of the milling head into die forged blank of the crankpin, in case of this particular crankshaft is removed changeable on its circumference layer of the material having thickness of \( a_p = 2.25 - 3.6 \text{ mm} \), which results from cylindricity deviation of the crankpin’s blank. Milling parameters during penetrating movement are: peripheral cutting speed of the milling head (equal to the cutting speed) \( v_0 = v_c = 100 \text{ m/min} \) and feed rate of the milling head \( f = 2.4 \text{ mm/rev} \). During milling of the crankpin, the cutting speed changed in range of \( v_c = 98.06 - 100.5 \text{ m/min} \), while the course of this variability variation is shown in Figure 4. Such course of the cutting speed \( v_c \) results from changes of the distance between rotation axis of the crankshaft and the tangency point of the milling head with the machined crankpin, and changes of the angle \( \psi \), which determines position of axis of the crankpin with respect to axis of rotation of the milling head, which occurs during a single rotation of the crankshaft (during machining of the crankpin on complete circumference).
Assumed rotational speed of the crankshaft equal to \( n_{cs} = 2.5 \) rpm restricts simulation time to 24 s, i.e., to the time required to completion of one full rotation of the crankshaft.

To compare the shape of the crankpin as obtained from the geometric model and from the measurements, rotary milling operation of the crankpins of the diesel engine with 6 double cranks was carried out on the FRK 400 milling machine produced by Heller Co., using the internal milling head (the same as in the model) at rotational speed of the crankshaft \( n_{cs} = 2.5 \) rev/min, and rotational speed of the milling head \( n_{mc} = 75.8 \) rev/min. Measurements of roundness profile of the machined crankpin No. 3 were carried out on a special type of coordinate measuring machine ADCOLE 1200-SH 1200 in 21 parallel planes, equally distributed every 2 mm. Coordinates of 720 points spaced at 0.5° were collected in every plane.

To obtain accurate assessment of cylindricity profile of the crankpin’s surface after the machining, a strategy of measurements of the roundness profile [1] was used, which allowed to obtain a distribution of measuring points, enabling mapping of the surface the most similar to its actual state. In Figure 5a presented is cylindricity profile of the crankpin obtained from geometric model, while in the Figure 5b profile of the real crankpin after the machining is shown.

Cylindricity deviation of the crankpin evaluated from the geometric model amounted to \( \Delta_{C}L \) \( r_{cp} = 0.022 \) mm and is nearly sevenfold smaller than the cylindricity deviation obtained from measurements of the real crankpin, which in case of the crankpin No. 3 amounts to \( -\Delta_{C}L \) \( r_{cp} = 0.152 \) mm. In practice, the measured deviation of the cylindricity consists of: relative changes in the diameter of the cylindrical workpiece, roundness deviation specified in various cross-sections, and eccentricity of roundness profiles with respect to associated (nominal) axis of the workpiece. As it turns out, number of the points describing trajectory of the analyzed points \( \ell_{p} \) has a significant effect on cylindricity deviation of the crankpin, evaluated from the geometric model. In case of the analytical method described in study [7], this number amounted to 10915 points, and is a slightly more than 4.5 fold higher than 2400 points used in the geometrical method. On the other hand, method of combining these points with a polyline or spline curve seems to be a secondary issue.

The Figure 6 additionally shows the profile of generating line for the crankpin from the model and from the measurements. Profiles of the generating line were made for the angular position of \( 0^\circ \), i.e. position for penetration of the milling head into machined crankpin, while for the crankpin obtained from the measurements, also for the angular position of \( 180^\circ \). Additionally, with fine line are marked radii of reference cylinders of the smallest zone \( r_{cp \text{MZCY}} \), which in case of the model of the crankpin is equal to \( r_{cp \text{MZCY}} = 45.697 \) mm, while in case of the measurements is equal to \( r_{cp \text{MZCY}} = 45.709 \) mm.
Figure 5. Cylindricity profile of the crankpin’s surface: a) based on the geometrical model – ΔCYL $r_{cp} = 0.022$ mm; b) measured on the machined crankpin No. 3 – ΔCYL $r_{cp} = 0.152$ mm [7]; Magnification of the deviations relative to the reference cylinder is 100×

Figure 6. Profile of the generating line of the crankpin: a) profile drawn on the base of the geometrical model for angular position 0°, b) profile for the machined crankpin No. 3 for angular position 0° [7], c) profile for the machined crankpin No. 3 for angular position 180°; Magnification of the deviations relative to the reference cylinder is 100×
4. CONCLUSIONS

Research conducted within the framework of presented study has enabled the evaluation of the shape of the crankpin after machining with the use of geometric method developed by the authors, based on 3D parametric model of rotary milling operation of the crankpin with suitably defined geometric constraints.

Profile of path of the points analyzed in the model on the edges of cutting inserts of the milling head having form of spline curve based on 2400 points has introduced a certain inaccuracy to the model, which to some extent results from nature of this curve, and number of points for tracking function available in the CAD system. Usage of slightly more than 4.5 fold smaller number of the points in the geometrical method, comparing to the analytical method [7], leads to the increase in the cylindricity deviation with 46.7 %. Evaluated cylindricity deviation for the geometric model amounted to $\Delta CYL_{rcp} = 0.022$ mm, and is nearly sevenfold smaller than measured deviation of cylindricity $\Delta CYL_{rcp} = 0.152$ mm, for the crankpin after machining with the same cutting parameters and with use of the same milling head. It should be explained by high and variable cutting forces due to changing cross-section of the cutting layer and changing depth of the cut, resulted from significant cylindricity deviations of the forged crankpin. Moreover, it should be also explained by limited stiffness of the crankshaft, despite the fact that each time the distance between the machined crankpin and the support elements was maintained to be constant.

REFERENCES

MODELOWANIE GEOMETRYCZNE FREZOWANIA OROTOWEGO CZOPÓW WAŁÓW KORBOWYCH

Streszczenie

W artykule przedstawiono modelowanie geometryczne obróbki zgrubnej czopów korbowych wału silnika spalinowego metodą wewnętrznego frezowania obrotowego, tj. głowicą frezową z płytkami skrawającymi skierowanymi do wewnątrz. Opracowano geometryczny model tej operacji obróbki, tj. wykonano model wału korbowego i głowicy frezowej w systemie CAD. W tak zaprojektowanym zespole zdefiniowano odpowiednie więzy geometryczne i określono wzajemną ruchliwość obu elementów. W wyniku symulacji obróbki określono kształt czopa po frezowaniu obrotowym, a tym samym dokładność obróbki.

Słowa kluczowe: modelowanie CAD, frezowanie obrotowe, wał korbowy, wewnętrzna głowica frezowa