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Strength and geometry parameters accuracy improvement of
3D-printed polymer gears

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Abstract. The study is concentrated on the topic of 3D-printed polymer gears quality
improving issues in terms of both mechanical strength and geometric precision at the
production by FDM process. The conception of gears radial 3D-printing based on functional
dimensional communications modelling between the basic and gear elements by string-mesh
structure forming of even- and uneven numbered layers; printing gear layers are represented as
stretched string system, pairwise and symmetrical placed related to the reference hole axis.
Tangential dimensional communication of bidirectional tangent lines to generating circle was
applied to the evolvement gears profiles forming. Formation of the gears tooth root on the
basic circle accompanied with string-mesh layer structure forming will provide quality gears
improvement.

1. Introduction

3D-printing is effective, emerging and integrative technique of well-timed in-process equipment
maintenance and adaptation due to opportunity to create demanded parts group including gears [1-14].
Gears accuracy is subject to determination of the International Standard [15] according to 12 gears
accuracy rating by such tolerances as kinematic accuracy, both contact and gear backlash fluency. The
standard does not limit gears material type. The following polymers features as low elastic modulus,
significant linear expansion coefficient, shrinkage at the stiffening, parts dimensional instability led to
the fact that polymer gears can meet challenge of 8…12 accuracy rating. One of the typical
examples of workpiece drawing of straight-toothed gear with surface finish rating indication is
presented in figure 1.

It is known 3D-printing is multiple-stage process including at least such production steps as model
design, its transformation (slicing) to the control G-codes and the printing. The slicing stage is of the
most practical interest because the parts accuracy depends on model transformation precision to G-
code. In the typical slicing software the conventional three-axis coordinate grid is used. This limitation
is logical defined by Z-fixed building table movements. Consequently, the main drawback of this
approach is parts accuracy depending on the nozzle diameter, ranged from 100 to 1000 µm, and
additionally on both the used thermoplastics materials and cooling procedure conditions [10-11].
It should be stressed technological failure of any post-processing (polishing, smooth finishing and etc.)
in respect to 3D-printed polymer parts. Therefore, as early as the modelling and slicing stages all
technological approaches and limitation should be accounted, and specifically by mathematical basics
of transformation as well as used 3D-printer parameters.
As it exemplified in [16] the ABS-plastics gears, which were FDM-produced by means three-axis
strategy and 400µm-nozzle diameter printer, correspond to 15 accuracy rating. It is reasonably for
disconnected elements general tolerance only.
2. Problem statement

Conventional software using (Kisslacer, Slic3r and etc.) does not in full support demanded parts quality, in final causing such possible defects occurrence as interlayer cracks, stair-step effect on the surface, cavities and etc. [3, 6, 10, 11, 16], negative resulted in lack of parts strength. Therefore alternative slicing algorithm basics development is one of the 3D-area research mainstreams.

The two main studied approaches in terms of gears geometry performance improvement have been recently described – one of them is based on spherical trigonometry application [7], the second - deals coordinated transformation [7-9]. Also both software and technical solutions supported multi-directional (five- and seven-axes) building table moving including tilting and rotating are known [13-14]. Such approaches aimed to support material reduction as well as overhanging structures avoiding are reasonable for complex shape parts 3D-printing. In mentioned above studies alternative solutions incompleteness of path planning strategy issues at the curved parts FDM-printing process is stressed.

In furtherance of ideas early presented in [7, 11, 12] in relation of additive produced gears for both geometrical precision improving and strength increasing purposes the follow is offered:

- To identify gears coordinate system;
- To define the shortest functional dimensional communications with basic elements in the gears coordinate system;
- To actualize FDM-techniques as well as slicing software based on dimensional communications symmetrical materialisation by filaments strings.

3. Theory

A gear consists of two working elements: a basic element involved the basic design datum which defines the gear position in the items mechanism; and a sectional involute element as an actuating element aimed to gears rotation transformation. The generalized design datum set which is identified by a set of main design datum that constrain the detail of six degrees of freedom - three linear and three angular. The basic element consists of three bases (figure 2): the \( A_4 \) base – the axis of cylindrical hole - has informativity 4, that limits two linear motion to the axis mutually perpendicular directions and two angle ones around them. The \( B_1 \) base as the symmetry plane of the prismatic part limits the gear moving along the \( A_4 \) base axis, informativity is 1. The base \( C_1 \) - the symmetry plane of the gear prismatic key way – confines additional angle gear moving, informativity is also 1.

![Figure 1. Workpiece drawing of a straight-toothed gear](image-url)
The basic three design datum set \( A4B1C1 \) limits six freedom degree of the gear shown in the base indicator (figure 2c); at the same time neither of six moving is doubled. This design datum set forms Cartesian coordinates system \( OX2Y\theta Z4 \) of the gear; their informativity is passed to \( Z4, X2 \) and \( Y\theta \) (zero) coordinate axis. The informativity of coordinate axis shows the opportunity to set two linear and two angular coordinates; and relating to \( X2 \) axis – one linear and two angular ones. Summarizing, six coordinates are enough in case of the sectional involute element for uniquely definition of the gear position in the \( OX2Y\theta Z4 \) coordinate system. Therefore, it is unreasonable to set any coordinate relating \( Y\theta \) coordinate axis having the zero informativity and lead to both redundant over-positioning and location uncertainty.

A sectional involute element also has own auxiliary coordinate system \( O'X'2Y'\theta Z'4 \) formed by the auxiliary element bases. The first auxiliary base is \( G4 \) axis of the outside cylinder materializes the basic gear element diameter \( d_b \). The lines, tangent to the basic cylinder, form involute tooth profile. The \( G4 \) base axis is the \( Z'4 \) auxiliary coordinate system axis at the same time. The second auxiliary base is the \( K1 \) symmetry plane of a tooth, which envelopes the \( X2 \) basic coordinate gear system and limits the element movement around the \( Z'4 \) axis; its informativity is 1. So, the total informativity of the \( G4 \) and \( K1 \) auxiliary bases is 5.

To form the full auxiliary 3D- coordinate system \( O'X'2Y'\theta Z'4 \), the \( B1 \) main base was used. It is symmetry plane of the outside prismatic element, which limits not only the \( A4 \) main base length but the width gear ring, respectively it serves as the \( B1 \) auxiliary base with missing informativity 1. The indicator of the \( G4B1K1 \) auxiliary bases set is shown in figure 2d. It includes linear and angular gear element freedom degrees limited by the bases, and also the \( O'X'2Y'\theta Z'4 \) auxiliary coordinate system which was formed by the bases. The auxiliary coordinate system axis of the gear element needs to be
in line with the $OX2Y\theta Z4$ basic coordinate system axis, which was formed by the main design datum set.

According to the classic engineering technique [17-20], the auxiliary coordinate system of the gear element has six deviations – six zero-point coordinates in relation to basic coordinate gear system: three linear coordinate of the $O'$ datum point at the $\theta=EXO'$, $\theta=EOY'$, $\theta=EOZ'$ auxiliary system and three angular axis coordinates of the $\theta=EX$, $\theta=EA$, $\theta=EZ$ auxiliary system. All six zero-point coordinates are limited by TCR circular runout, TCA face motion variation and TPS symmetry (figure 1).

4. Results

Based on the above-mentioned it can be concluded that additive techniques have the advantages over conventional ones due to processing datum sets. But, in the case of 3D-printing process configuration in terms of the $OX2Y\theta Z4$ basic coordinate system of the basic gear design datum in contrast to the $O_pX_pY_pZ_p\theta$ printer system one, the gear geometrical accuracy will increase due to the numerical coordinates values reduction of printing parts model points (figure 2b).

At the same time, one of the 3D-printers disadvantages is the contravention of the base and the inversion unanimity principle – it is the basic engineering principle of quality providing during full product life circle.

While following to the bases unanimity principle, the design datum needs to be transformed to the processing datum. In actual practise at the model processing the only $B1$ flat base with informativity 1 (figure 2c) from the three main $A4B1C1$ ones is used as the design datum. This base is superimposed of the 3D-printer building table, as a result the $B1$ base informativity is raising to 3 limited freedom degrees $B3$, and also the $A4B3C1$ design datum set is transformed to both statistical undefined one ($4+3+1=8-6=2$) and redundant over-positioning at the two angular motions around the $X_p4$ and $Y_p2$ printers coordinate axis placed at the 3D-printer plane.

To avoid the over-positioning it is recommended to equip the printer with the building table 3 (figure 2a) as the functional locating tool, which is regulated by the two-angle. The work locating plane is positioned normal to the $Z_p\theta$ printer axis, which is parallel to the nozzle movement. The table central hole axis can be used as the $J2$ auxiliary base whereby the $X_p4$, $Y_p2$, $Z_p0$ zero-point coordinates of the $OX2Y\theta Z4$ gear coordinate system are setting at the 3D-operation procedure.

Moreover, following to the inversion principle the gear needs to move at the producing stage by the same way as during the operation one that is turn about the $A4$ basic hole axis. It is impossible for 3D-printers based on conventional Cartesian coordinates system.

The facts listed above are agree with conclusions presented in [13] about reasonability of 3D-printers construction based on cylindrical coordinate system equipped by rotating table for such axisymmetric bodys production as gears.

The identifying advantage of the decision is what the bases and the actuating surfaces gears are formed at the two interconnecting layer transition for each printing layer. At the first transition filament strings needs to connect numerous point of the basic base with opposite lied ones of the $G4$ gear primary auxiliary base by the shortest radial dimensional connections. In order to reduce polymer shrinkage and symmetry principle support, dimensional connections between the basic and auxiliary gears bases should be done by the doubled way namely by two oppositely (under 180°), back and forth from the zero-point of the $OX2Y\theta Z4$ basic system placed dimensional connections – firstly, normal to $X2$ axis, then, parallel to it.

As a result, the opposed radial strait dimensional connections are materialized by points-to-points between the design and auxiliary database by molten filaments. During cooling procedure the filaments are shorten forming stretched strings which are centered the $OZ4$ axis of the auxiliary gear base in relation to the $OZ4$ basic system axis. So, the radial string system of the basic element with both operation strength and increased accuracy is formed.

Numerous melted lines form such dimensions as $A4$ basic hole diameter ($D_a$), two (for gears symmetry) $C1$ basic gear key ways with $L$ length and also the $d_b$ basic diameter of the $G4$ auxiliary base transferring it from design (calculated) type to materialize (inspectable) one.
At the second transfer of the first uneven layer the involute tooth profiles will form by tangential filament strings, which are tangent to the $G4$ auxiliary base and materialize at the first transfer. While hardening filament layers will form strings, which fix tooth root on the $G4$ auxiliary base circumference. These strings tighten left and right tooth profiles forming string-mesh tooth structure resulted in gears strength and accuracy increasing. Alternating on the symmetry principle of the each opposing tooth construction with a phase shift of 180°, a fully toothed element of the first printing layer is formed.

The second (even) gear layer is based on a similar technology, differing only in various orientation angles of filaments, materialized the dimensional connections for the mesh structure formation of intersecting strings of the odd and even lines to increase both accuracy and strength of the wheel. The strings crossing angle of the basic elements depends on the gear size, but needs not exceed 10°. The crossing angle the tooth strings is $(180°-2\alpha)$, where $\alpha$ is the angle of the involute tooth profile determined by the initial contour [6]

**Conclusion**

Despite wide spread additive techniques application and FDM-printing in particularly as the one of the most cost-effective parts prototyping and production methods the typically 3D-printed polymer gears do frequently not agree with both the standardized accuracy norms and working strength parameters. Aimed to the both FDM-printed gears geometry accuracy and strength improvement it is offered:

- To exploit the cylindrical coordinate system based on the design datums set which define the gear position in relation to the shaft at the operation as the 3D-printers software foundation. It provides both the abidance of the bases unanimity principle and the linear and angle coordinates reducing of the gears actuating element. The primary auxiliary base of the sectional gear involute element should be the base circle, which transforms from the calculated base to the materialized as well as inspectable one. According to the inversion principle it will allow to improve accuracy rating of 3D-printed polymer gears.
- Filament position should materialize the opposed radial dimensional communications between the design and auxiliary database as well as tangential ones between the gear base diameter and involute tooth profiles.

The identifying advantage of the decision is what the bases and the actuating surfaces gears are formed at the two interconnecting layer transition for each printing layer in order to polymer shrinkage reduction accompanied by symmetry principle supporting. At the cooling stage filament layers will form hard string symmetry resulted in gears strength increasing.

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