SYNTHESIS OF THE STRUCTURE OF THE TECHNOLOGICAL PROCESSES OF MAKING SPATIALLY MODIFIED COUPLING TOOTH DEPENDING ON THE CONDITIONS OF THE SHAFT AXE MISALIGNMENT

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Abstract. *In the given work features of synthesis of structure of technological process of manufacturing of the spatially-modified teeth gear coupler depending on conditions of a warp of axes of connected shaft are considered. Researches of deviations of geometrical parameters of the spatially-modified teeth gear couplers from nominal values are executed. Variants of structures of technological process of manufacturing of teeth gear couplers depending on conditions of a warp of axes of shaft are resulted and recommendations about their compilation are given.*
Key words: *spatially modified couplings teeth, approximated geometry, the method of spatial rolling-in, technological process structure.*

1. Introduction

Toothed couplings for combining equiaxial shafts, having angular and radial axial distortion are widely used in transportation system' transmission. They usually operate under difficult load condition with the high vibration frequency [1]. At present a great number of versions of the coupling tooth geometry which solve functional tasks have been developed. The spatially modified tooth geometry, which provides load balancing in the tooth action and the tooth linear contact [2, 3, 4] according to the coupling turning angle, is the most efficient geometry of the tooth working surfaces.

There are a lot of ways and methods of machining of the coupling spatially modified teeth to make spatially modified coupling tooth geometry [4, 5, 6, 7]. These methods allow making of the spatially modified coupling tooth geometry for the particular angles of misalignment of the axes of the gear coupling elements. There are no general recommendations as to design of the structural versions of technological processes for the general range of misalignment of the gear coupling elements. To reduce the cost of making of gear coupling and raise the quality of their making the rational structuring of the versions of the technological processes is of great importance.

The goal of the work is to reduce the cost of making of the gear couplings with the spatially modified tooth geometry and raise the quality of their making at the expense of synthesis of the rational structure of the technological process for the given limit of misalignment of the axes of the coupling elements by the successive approximation of the machining process parameters to the 2^{nd} mode of Olivier.

The Olivier's second mode of making of spatial gearings with the linear touch of the tooth surfaces is based on two conditions [1]:

1. Cutting of the tooth surface of one of the mechanism links (gear coupling) is to be done by the instrumental surface which completely coincides with the surface of the other link in the gear (gear coupling).

2. The structure of the tool and work piece relative motions during making of the coupling teeth on the technological system must be same as in the gear mechanism (gear coupling) during the operation.

According to the goal the following tasks have been defined for solving: to examine the characteristics of the synthesis of the structure of the technological process of making of spatially modified coupling teeth depending on the conditions of misalignment of the axes of shafts which are connected; to research the deviations of the geometrical parameters of the spatially modified coupling teeth of the nominal values; to develop versions of the structures of the technological process of making the coupling teeth depending on the conditions of misalignment of the axes and give recommendations as to their making up.

2. General information

To do the synthesis of the structure of the technological process aimed at making of the spatially modified coupling teeth depending on the conditions of misalignment of the axes of the shafts they connect the universal structure of the technological process has been developed. It is shown in the fig.1 and consists of the following operations:

1 Preliminary machining (milling by copying with the structure of the motion of the gear disk milling cutter along the special line of the initial contour);

2. Rough machining (milling by breaking –in with the structure of the motion of the hob gear cutter along the special line of the initial contour);

3. Semi-finishing work (milling by copying of the module disk milling cutter or breaking-in by the hob gear cutter, machining which provides complete identity of the kinematic structure, fulfillment of the Olivier's 2nd mode 2nd condition);

4. Finishing (pull broaching by the method of braking-in with the special toothed pull broaching with the complete identity of the tool geometry, fulfillment of the 1st condition of Olivier's 2-nd mode);

5. After finishing (honing by the spatial breaking-in with the help of the gear hone of the internal gearing, fulfillment of 2 conditions of Olivier's 2nd mode);

6. Fine finishing (is done by the spatial breaking-in with the help of the special tool, fulfillment of 2 conditions of Olivier's 2nd mode).

This general universal structure of the technological process allows making up of the particular versions of the rational technological processes for certain limits of the angles of the coupling element axe misalignments. Thus, for example, we do not need all the operations of the universal technological process for the small angles of the coupling element axe misalignment. We need only their partial implementation. That is why extra research work is needed. To do the research let us define the values of increment of the coordinates of the real surfaces in respect to the nominal ones.

The nominal tool surface :

$\vec{r}_{01,H} = \vec{r}_{01,H}(u,v)$ is given in the coordinate system π_{01} (1)

Then the coordinates of the real tool surface with taking into account the errors described by the increment of the radius vector $\Delta\,\vec{r}_{01}$ are as follows:

$$\vec{r}_{01,p} = \vec{r}_{01,H} + \Delta\,\vec{r}_{01}. \quad (2)$$

The tooth surface series is defined by the following equation:

$$\vec{r}_{02,p} = \vec{r}_{02,p}(u,v,\Delta\,\vec{r}_{01},\varphi,\psi), \quad (3)$$

where φ и ψ - motion independent parameters.

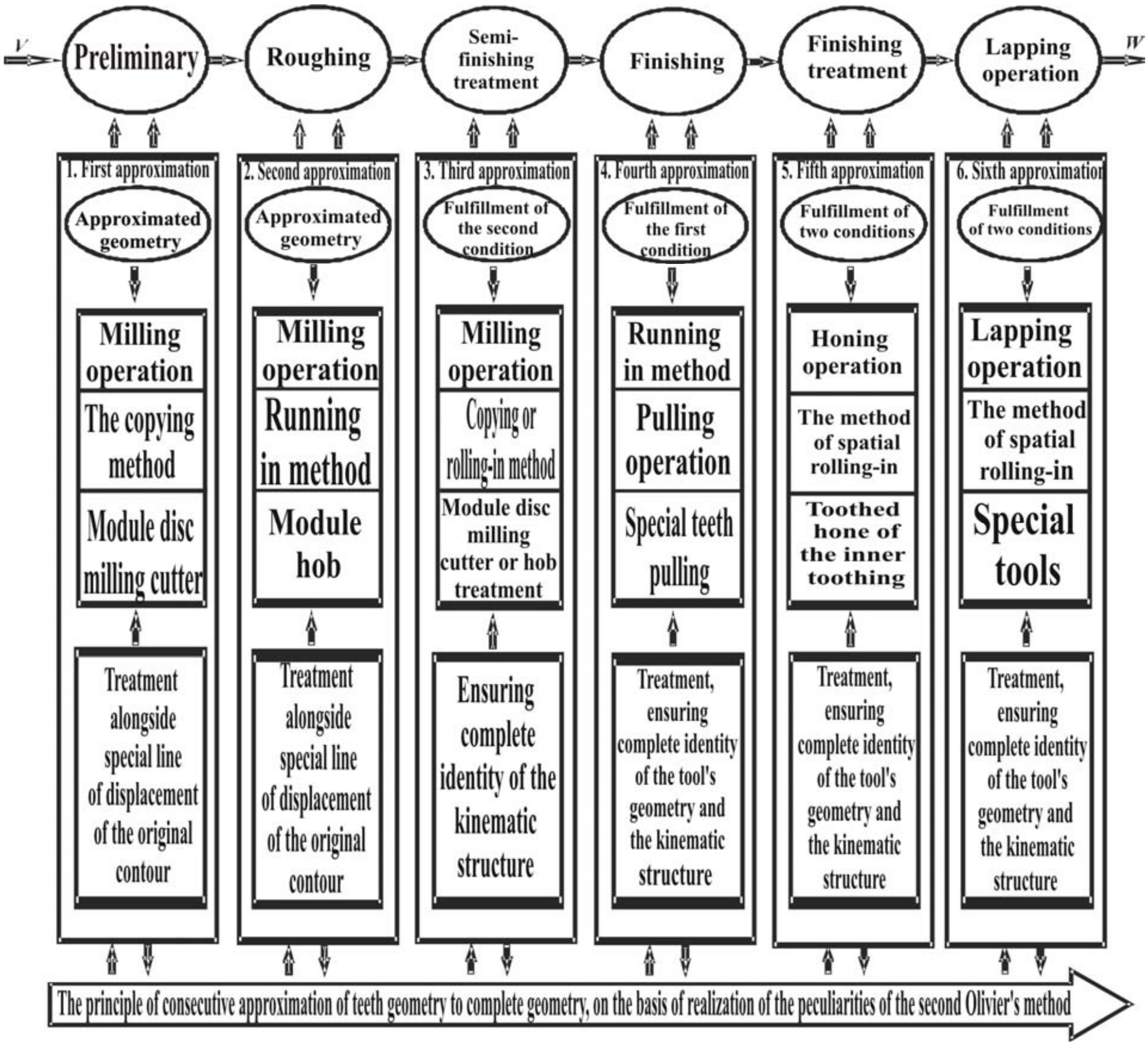

Fig. 1. The diagram of consecutive approximation of geometry of coupling's teeth towards precise spatially modified geometry with regard to operations of the technological process (general universal structure of the technological process)

At the successive fixed value of the parameters φ и ψ, the equations (3) define the tool real surface in the system π_{02}. The line of the contact of the tool with the surface of the spatially modified tooth geometry will be found if the dependence among the following parameters is defined:

$$u = u(\varphi, \psi); \tag{4}$$

$$v = v(\varphi, \psi). \tag{5}$$

Equations (3) and (4), (5) which are examined together under the successive fixed value φ or ψ, define the series of the contact lines of the system π_{02}.

As to the equations (2) and (3), let us use the fact that the inter-enveloped surfaces have a single tangential plane. The tangential plane to the enveloped surface is defined by the vectors [1]:

$$\frac{\partial \vec{r}_{02,p}}{\partial u}\frac{\partial u}{\partial \varphi}+\frac{\partial \vec{r}_{02,p}}{\partial v}\frac{\partial v}{\partial \varphi}+\frac{\partial \vec{r}_{02,p}}{\partial \varphi}, \tag{6}$$

$$\frac{\partial \vec{r}_{02,p}}{\partial u}\frac{\partial u}{\partial \psi}+\frac{\partial \vec{r}_{02,p}}{\partial v}\frac{\partial v}{\partial \psi}+\frac{\partial \vec{r}_{02,p}}{\partial \psi}. \tag{7}$$

The tangential plane to the tooth surface, the parameters of which are u and v, is defined by the vectors $\partial \vec{r}_{02,p}/\partial u$ and $\partial \vec{r}_{02,p}/\partial v$. For the vectors to be within the tangential plane they should be complanar and the mixed product of all the vectors should be equal to zero. Thus:

$$\left[\frac{\partial \vec{r}_{02,p}}{\partial u},\frac{\partial \vec{r}_{02,p}}{\partial v},\frac{\partial \vec{r}_{02,p}}{\partial \varphi}\right]=0, \tag{8}$$

$$\left[\frac{\partial \vec{r}_{02,p}}{\partial u},\frac{\partial \vec{r}_{02,p}}{\partial v},\frac{\partial \vec{r}_{02,p}}{\partial \psi}\right]=0. \tag{9}$$

The required dependencies (4) and (5) are found from the equations (8) and (9).

Equations (8) and (9) can be interpreted in the following way :

$$\frac{\partial \vec{r}_{02,p}}{\partial \varphi}\left(\frac{\partial \vec{r}_{02,p}}{\partial u}\times\frac{\partial \vec{r}_{02,p}}{\partial v}\right)=v_{02}^{(01,02,\varphi)}\, n_{02}=v_{02}^{(02,01,\varphi)}\, n_{02}=0, \tag{10}$$

$$\frac{\partial \vec{r}_{02,p}}{\partial \psi}\left(\frac{\partial \vec{r}_{02,p}}{\partial u}\times\frac{\partial \vec{r}_{02,p}}{\partial v}\right)=v_{02}^{(01,02,\psi)}\, n_{02}=v_{02}^{(02,01,\psi)}\, n_{02}=0\cdot \tag{11}$$

$v_{02}^{(01,02,\varphi)}$ и $v_{02}^{(02,01,\varphi)}$ in these expressions – speed of the motion of the tool relative to the spatially modified tooth geometry and of the spatially modified tooth geometry relative to the tool under the fixed value of the motion parameter ψ. Similarly to $v_{02}^{(01,02,\psi)}$ и $v_{02}^{(02,01,\psi)}$ - is the corresponding speed of the relative motion of the links under the fixed value of the motion parameter φ. The normal vector to the surface of the spatially modified tooth geometry in the system π_{02} is as follows:

$$n_{02}=\frac{\partial \vec{r}_{02,p}}{\partial u}\times\frac{\partial \vec{r}_{02,p}}{\partial v}. \tag{12}$$

Equations (10) and (11) are right if the normal vectors and speed vectors of the relative motion are examined not in the system π_{02}, but in the system π_{01}, related to the tool, or in the system π_i, related to the tooth nominal coordinate system. In this case [1]:

$$n_r\, v_r^{(01,02,\varphi)}=n_r\, v_r^{(02,01,\varphi)}=0; \tag{13}$$

$$n_r\, v_r^{(01,02,\psi)}=n_r\, v_r^{(02,01,\psi)}=0, \tag{14}$$

Where $r = 01;\ 02$.

In number of cases the expressions (10) and (11) simplify the defining of the geometrical parameters of the real surface of the spatially modified tooth geometry.

In the coordinate recording the equation of the real surface of the spatially modified tooth geometry if $r = 01$ is as follows:

$$\left.\begin{aligned} &x_{02,p} = x_{02,p}\left(u, v, \Delta\vec{r}_{01}, \varphi, \psi\right);\\ &y_{02,p} = y_{02,p}\left(u, v, \Delta\vec{r}_{01}, \varphi, \psi\right);\\ &z_{02,p} = z_{02,p}\left(u, v, \Delta\vec{r}_{01}, \varphi, \psi\right);\\ &n_{x01}v_{x01}^{(01,02,\varphi)} + n_{y01}v_{y01}^{(01,02,\varphi)} + n_{z01}v_{z01}^{(01,01,\varphi)} = 0;\\ &n_{x01}v_{x01}^{(01,02,\psi)} + n_{y01}v_{y01}^{(01,02,\psi)} + n_{z01}v_{z01}^{(01,01,\psi)} = 0. \end{aligned}\right\} \qquad (15)$$

The expressions $n_{x01}, n_{y01}, n_{z01}$ of the normal vector projection depend only on the type of the given tool surface.

The projections of the speed vector of the link relative motion are defined according to the expressions:

$$\left.\begin{aligned} v_{x01}^{(01,02,\varphi)} &= \frac{\partial x_{01,p}}{\partial \varphi},\\ v_{y01}^{(01,02,\varphi)} &= \frac{\partial y_{01,p}}{\partial \varphi},\\ v_{z01}^{(01,02,\varphi)} &= \frac{\partial z_{01,p}}{\partial \varphi}, \end{aligned}\right\}, \qquad \left.\begin{aligned} v_{x01}^{(01,02,\psi)} &= \frac{\partial x_{01,p}}{\partial \psi},\\ v_{y01}^{(01,02,\psi)} &= \frac{\partial y_{01,p}}{\partial \psi},\\ v_{z01}^{(01,02,\psi)} &= \frac{\partial z_{01,p}}{\partial \psi}. \end{aligned}\right\}.$$

Here the relative speed vectors $v_{01}^{(01,02,\varphi)}$ и $v_{01}^{(01,02,\psi)}$ are defined by the coordinate system location, motion parameters, and, that goes without saying, do not depend on the side surface type.

The special cases of the equations of the real surfaces of all existing machining schemes follow the obtained general equations (15) of the real surfaces of the spatially modified tooth geometry.

Expression (15) is recorded in the following way:

$$\left.\begin{aligned} x_{02,p} &= x_{02,p}\left(\varphi, \psi, \vec{\Delta}_{\Pi}, \vec{\Pi}\right);\\ y_{02,p} &= y_{02,p}\left(\varphi, \psi, \vec{\Delta}_{\Pi}, \vec{\Pi}\right);\\ z_{02,p} &= z_{02,p}\left(\varphi, \psi, \vec{\Delta}_{\Pi}, \vec{\Pi}\right), \end{aligned}\right\} \qquad (16)$$

Where $\vec{\Delta}_{\Pi}$ - the initial error vector;

$\vec{\Pi}$ - the vector of the nominal geometric parameters of the motion structure.

With expression (16), where $\vec{\Delta}_{\Pi} = 0$, the equations of the nominal surfaces of the spatially modified tooth geometry can be obtained (fig.2):

$$
\left.\begin{aligned}
x_{02,H} &= x_{02,H}\left(\varphi, \psi, \vec{\Pi}\right);\\
y_{02,H} &= y_{02,H}\left(\varphi, \psi, \vec{\Pi}\right);\\
z_{02,H} &= z_{02,H}\left(\varphi, \psi, \vec{\Pi}\right),
\end{aligned}\right\} \tag{17}
$$

where $x_{02,H}$, $y_{02,H}$, $z_{02,H}$ are the coordinates of the nominal surface of the spatially modified tooth geometry.

After the substitution of the real values of the geometric parameters of the evolvent teeth and forming kinematics the equation of the spatially modified coupling tooth surface in the coordinate recording is as follows [2, 3, 4]:

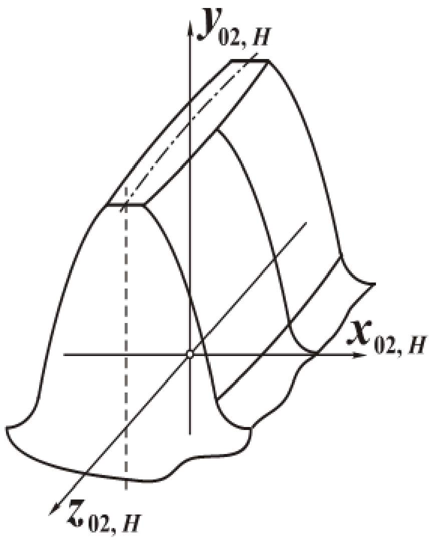

Fig. 2. Coupling tooth nominal spatially modified geometry

$$
\left.\begin{aligned}
x_{02,H} &= x_{01,H} + 2A_1 r_b \cos\psi \sin^2\frac{\omega}{2},\\
y_{02,H} &= y_{01,H} + 2A_1 r_b \sin\psi \sin^2\frac{\omega}{2},\\
z_{02,H} &= A_2 - \left(x_{01,H}\cos\psi + y_{01,H}\sin\psi\right)\sin\omega.
\end{aligned}\right\} \tag{18}
$$

Here

$$
A_1 = \cos(\psi + \varphi - \varphi_c)\left[ctg(\psi + \varphi - \varphi_c) + \varphi\right],
$$

$$
A_2 = \frac{r_b \cos\omega tg \,{}^{\omega}\!/_{2}}{\sin(\psi + \varphi - \varphi_c)}.
$$

In the expression (18) the values $x_{01,H}$ и $y_{01,H}$ are defined from the system of equations (19) and are the parameters of the evolvent profile of the bush teeth:

$$
\left.\begin{aligned}
x_{01,H} &= r_b\left[\sin(\varphi-\varphi_c)-\varphi\cos(\varphi-\varphi_c)\right],\\
y_{01,H} &= r_b\left[\cos(\varphi-\varphi_c)+\varphi\sin(\varphi-\varphi_c)\right],\\
z_{01,H} &= r_b tg\vartheta.
\end{aligned}\right\} \qquad (19)
$$

where r_b – the tool main cylinder radius;

φ - the evolvent parametric angle;

ν - the point parametric angle in the longitudinal section.

Here

$$
\varphi_c = \frac{\pi}{2z} + inv\alpha_w,
$$

where z – number of teeth;

$inv\alpha_w$ - the evolvent angle corresponding to the profile point on the reference cylinder.

The calculation of the coordinate increment of the real surfaces of the spatially modified tooth geometry relative to the nominal surfaces is based on the equations (17) and (18):

$$
\left.\begin{aligned}
\Delta x_{02,H} &= x_{02,p} - x_{02,H};\\
\Delta y_{02,H} &= y_{02,p} - y_{02,H};\\
\Delta z_{02,H} &= z_{02,p} - z_{02,H},
\end{aligned}\right\} \qquad (20)
$$

where $\Delta x_{02,p}, \Delta y_{02,p}, \Delta z_{02,p}$ - is the increment of the coordinates of the real surfaces relative to the nominal ones.

After the values of the parameters of the coordinate increment of the real surfaces of the spatially modified tooth geometry relative to the nominal values are defined, we define the interaction between these increments and rated errors of the spatially modified tooth geometry and develop the methods of reduction of errors in making the spatially modified tooth geometry.

Fig. 3 shows the dependence of the increment $\Delta x_{02,H}$ of the coordinate of the real $x_{02,p}$ and nominal $x_{02,H}$ tooth surface according to the operations N with $z = 22$, $m = 5{,}5$ мм, $\omega = 1{,}5^\circ$, $B = 20$ мм. When analysis of the increment dependencies $\Delta x_{02,H}$ of the real coordinate $x_{02,p}$ and nominal $x_{02,H}$ of the tooth surface according to the operation N for different angles of misalignment of the coupling axe angles is done, we can give the recommendations as to making up the technological process structure. These recommendations are given in a table.

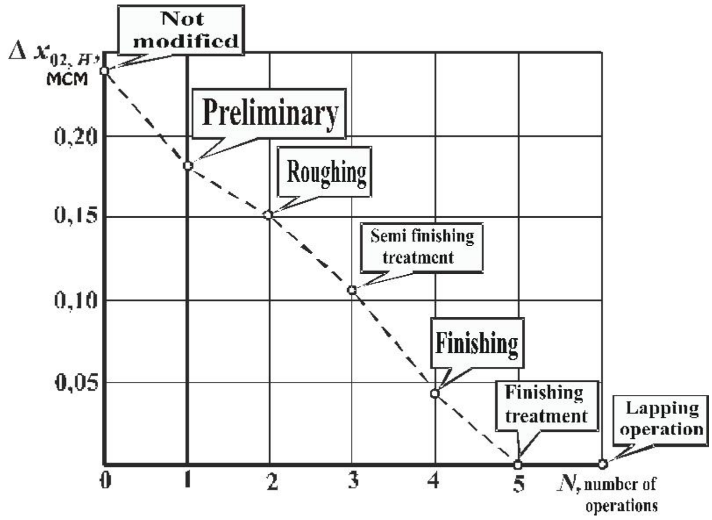

Fig. 3. Dependence of increment Δx 02,H of the coordinate of the real x 02 p and nominal x 02,H of tooth surface with regard to operations N at Z= 22, m=5.5.mm , B=20mm, ω= 1.5 °

Table

Technological process structure and dependencies on the axe misalignments

№	Values of the bush misalignments relative to the ring, degrees	Number of technological operations	Technological process structure
1	$0^{O} < \omega \leq 0{,}25^{O}$	5	W ⇒ (5) ⇒ V
2	$0{,}25^{O} < \omega \leq 0{,}5^{O}$	5, 6	W ⇒ (5) ⇒ (6) ⇒ V
3	$0{,}5^{O} < \omega \leq 0{,}75^{O}$	4, 5, 6	W ⇒ (4) ⇒ (5) ⇒ (6) ⇒ V
4	$0{,}75^{O} < \omega \leq 1{,}0^{O}$	3, 4, 5, 6	W ⇒ (3) ⇒ (4) ⇒ (5) ⇒ (6) ⇒ V
5	$1{,}0^{O} < \omega \leq 1{,}5^{O}$	2, 3, 4, 5, 6	W ⇒ (2) ⇒ (3) ⇒ (4) ⇒ (5) ⇒ (6) ⇒ V
6	$1{,}5^{O} < \omega \leq 2{,}0^{O}$	1, 2, 3, 4, 5, 6	W ⇒ (1) ⇒ (2) ⇒ (3) ⇒ (4) ⇒ (5) ⇒ (6) ⇒ V

The table reflects the versions of the technological process structures for different values of the bush axe misalignment relative to the ring.

4. Conclusions

To conclude, we would like to mention that the characteristics of the synthesis of the technological process structure of making the spatially modified coupling teeth depending on the conditions of the axe misalignment of the connected shafts are examined in the paper. The research work on the misalignment of the geometrical parameters of the spatially modified coupling teeth from the nominal values is done. The graph of the dependence of the increment of the coordinate of the real and nominal surface of the spatially modified tooth surface according to the operations is built. The rational versions of the structures of the technological process of making the coupling teeth depending on the conditions of the shaft axe misalignment are developed. The recommendations on their making up are given.

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СИНТЕЗ СТРУКТУРЫ ТЕХНОЛОГИЧЕСКИХ ПРОЦЕССОВ ИЗГОТОВЛЕНИЯ ПРОСТРАНСТВЕННО-МОДИФИЦИРОВАННЫХ ЗУБЬЕВ МУФТЫ В ЗАВИСИМОСТИ ОТ УСЛОВИЙ ПЕРЕКОСА ОСЕЙ ВАЛОВ

Гитуни А., Михайлов А.Н., Набиль Бен Фредж, Долгих А.С.

Аннотация. *В данной работе рассматриваются особенности синтеза структуры технологического процесса изготовления пространственно-модифицированной геометрии зубьев муфты в зависимости от условий перекоса осей валов. Выполнены исследования отклонений геометрических параметров пространственно-модифицированных зубьев муфт от номинальных значений. Разработаны рациональные варианты структур технологического процесса изготовления зубьев муфты, в зависимости от условий перекоса осей валов и даны рекомендации по их составлению.*

Ключевые слова: *пространственно-модифицированные зубья муфты, приближенная геометрия, метод пространственной обкатки, структура технологических процессов.*