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INFLUENCE OF WAVINESS PARAMETERS ON THE OPERATIONAL PROPERTIES OF CYLINDRICAL LARGE-MODULAR GEARS

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ABSTRACT: *The approach of determination of the waviness height on the surface of gears was developed in this paper. The analysis of surface microgeometry shows that significant waviness is inherent to the large-module cylindrical gears after machining with different types of cutting tools. There are a number of factors leading to this phenomenon: the initial state of the surface layer of the work piece being processed; the accuracy of locating and fixing the blank of the gear wheel and cutting tool; the geometry of the cutting tool and the kinematics of movement of the tool and the machined gear. All these aspects were taken into account and the expression was proposed which allows one to calculate total value of waviness* W_z *formed on the involute surface of a cylindrical gear. This expression is composed of all the listed components in accordance with the rules for summing random variables. The analysis of the research results shows that the main influence on the waviness during high-speed gear milling is exerted by the stiffness of the technological system, speed, feed, and the coefficient of formation of the surface layer. Verification of obtained theoretical equation demonstrated satisfying coincidence with experimental data observed in cases of gear milling with cemented carbide milling cutting tool and during high-speed gear milling of cylindrical gears with modulus m = 16 mm from 40X steel.*

KEYWORDS: waviness height, gear processing, milling hob, cemented carbide cutting tool, oscillations of the cutting tool.

INTRODUCTION

The operational properties of large-modular cylindrical gears mainly depend on the quality of machined surfaces of the gears' teeth, namely their roughness and, that even is more important, waviness of their surfaces. That is why the development of an analytical approach which allows one to predict a waviness height is of particular interest.

It is known, that among the main reasons for the waviness formation are the dynamic processes occurring during machining of cylindrical gears on gear processing machines which cause the appearance of self-oscillations and forced oscillations of the MTDTS (Machine Tool Dynamic Technological System). Among other factors that affect the formation of waviness of the surfaces of cylindrical gears during gear processing: the initial state of the surface layer of the workpiece being processed; the accuracy of locating and fixing the blank of the gear wheel and cutting tool; the geometry of the cutting tool and the kinematics of movement of the tool and the machined gear.

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A number of studies investigated the methods of determination of noise reasons connected with waviness and the specific features of the waviness impact on the performance of a gear pair. The authors of Sundar, S. *et al.* 2013 studied the effects of tooth surface waviness and sliding friction on the dynamics and radiated structure-borne noise of a spur gear pair. Their model predicts a 17 dB reduction in sound level if W_z value declines from 9 to 1 mkm. Other sources (Ishida, K. 1980, Hansen, B. *et al* 2006) also showed the decrease in sound at 10 and 7 dB while W_z drops from 9 to 1 and from 0,38 to 0,07 mkm correspondingly. Lately, Fourier analysis of bearing surface waviness has been widely used for determination factors leading to appearance of low-frequency noise in a gearbox (Wagaj, P. 2019). As authors reveal, such methods helps to find specific manufacturing drawbacks with the rotary table of the machine tool used in the finishing of the gear. In Günther Gravel, 2013 it was estimated that a tool error inherent to the gear machining will generate an impulses which matches the order of noise and that issues can be estimated using special software. A special technique of gear waviness analysis was developed also in Takeshi HORI, 2015. It was shown that the cyclical peak order of the waviness matched the peak order of frequencies of sound radiation from gears. As well as a quantitative correlation was found between the amplitude of peak order waviness and the pressure level of sound radiation from gears. The complex analysis of the cylindrical large-modulus hardened gear microgeometry formation conditions was performed in Timofeev, Yu. *et al* 2010. It was shown that when assigning proper parameters (roughness, waviness) of the contacting surfaces of cylindrical large-modulus hardened gears, the processing methods for ensuring these parameters are established as a function of hardness of machined gear.

METHODS

The method of determination of the total height of the waviness is explained in this section. Depending on the methods and conditions of gear processing, the degree of influence of the listed factors on the formation of waviness will be different. Thus, the average height of waviness formed on the involute surface of a cylindrical gear during gear processing is composed of all the listed components in accordance with the rules for summing random variables:

$$W_z = 1{,}2\sqrt{H_1^2 + H_2^2 + H_3^2} \qquad (1)$$

The component of the waviness height H_1 appears due to the initial state of the surface layer of the workpiece being processed during counter gear milling. Based on the difference in forces acting on the tool caused by the heterogeneity of the state of the surface layer of the workpiece and the dynamics of the process, as well as for the roughness, it can be determined by the formula (Yampolsky, L.S., 2006):

$$H_1 = \frac{c_y S^y \rho v^2 P\left[HB_{max}^n t^x p - HB_{min}^n (t - W_{z\,init} - R_{z\,init})^{x_{p0}}\right]}{HB_{av}^n\, j \sqrt{\left(1 - \frac{\lambda^2}{\omega^2}\right)^2 + Th^2\lambda^2}} \qquad (2)$$

where $W_{z\,init}$ - is the initial wave height (Fig. 1 a).

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In high-speed gear milling, the dispersion of the initial state of the surface layer leads to a dynamic change in the radial force, and, consequently, to forced oscillations of the cutting tool relative to the workpiece surface being machined (Yampolsky, L.S. 2006, Permyakov A.A. *et al* 2019).

During gear machining the vibrations of the cutting tool relative to the workpiece are the result of its radial, axial and tangential movements. Oscillations of the gear cutting hob can be represented as a system with three degrees of freedom (translational movement along the x, y and z axes).

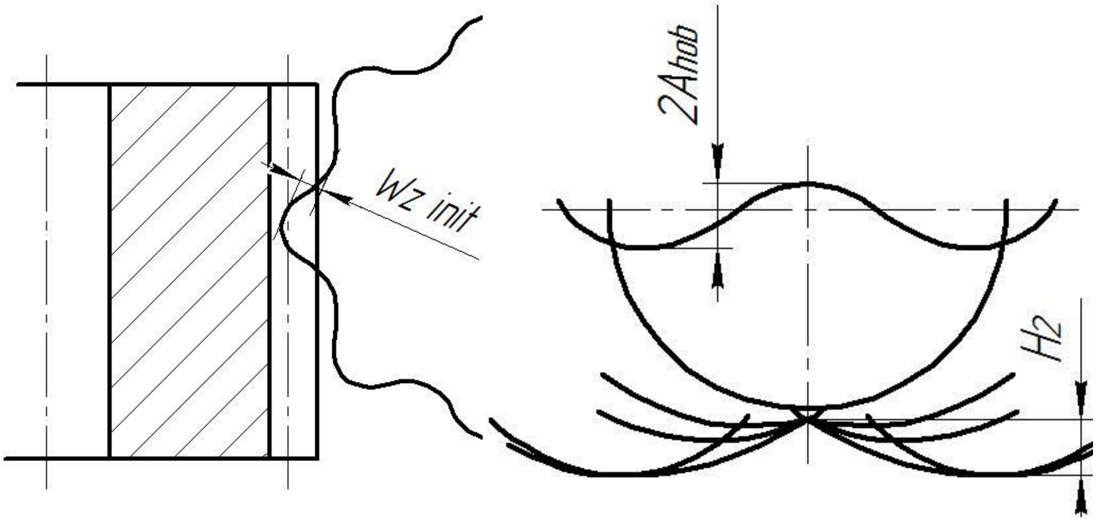

Figure 1 - Initial scheme for calculating the H_2 component during high-speed gear milling from forced oscillations of the cutting tool (a) and from its self-oscillations (b)

During high-speed gear hobbing, the radial runout of the cutting tool causes an oscillation of the radial force, leading to forced oscillations of the cutter axis (Fig. 1 b). The component H_2 of these fluctuations:

$$H_2 = A_{hob}\left\{1 - \cos\left[13{,}2\frac{v}{t}\sqrt{\frac{1}{Ahob}\left(\frac{1}{v}+\frac{1}{d}\right)}\right]\right\} \quad (3)$$

A change in the radial cutting force during high-speed gear milling leads to uneven wear of the cutting tool and the appearance of waviness on the machined surface of the gear profile.

So, as can be seen in gear milling, the shape of the cutting tool and the kinematics of its movement affects the waviness through the components H_1 and H_2.

The H_3 component is especially pronounced during intermittent high-speed gear milling in the form of the so-called kinematic waviness, which is determined by next equations:

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$$H_3 = \frac{D(1-\cos\delta)}{2\cos\delta} \quad (4)$$

where

$$\delta = \frac{180 l_0 v}{\pi v_{cr} D}, \quad (5)$$

Summing all expressions needed to determine H_1, H_2 and H_3 and performing mathematical transformations, we obtain an equation for determining the average wave height during gear milling.

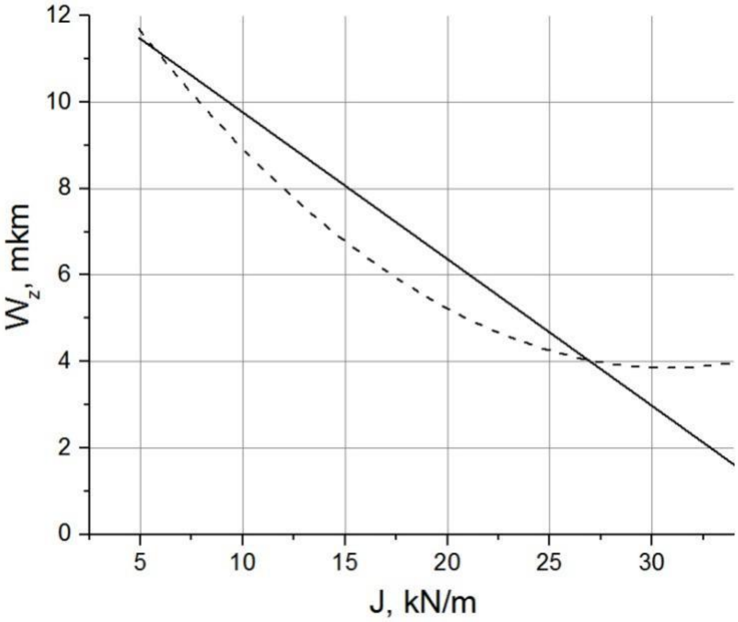
$$Wz = 1{,}2\sqrt{\left(\frac{c_y S^y \rho v^2 P[HB_{max}^n t^x p - HB_{min}^n (t - W_{z\,init} - R_{z\,init})^{x_{p0}}]}{HB_{av}^n\, j\, \sqrt{\left(1-\frac{\lambda^2}{\omega^2}\right)^2 + Th^2\lambda^2}}\right)^2 + \left(A_{hob}\left\{1-\cos\left[13{,}2\frac{v}{t}\sqrt{\frac{1}{A}\left(\frac{1}{v}+\frac{1}{d}\right)}\right]\right\}\right)^2 + \left(\frac{D(1-\cos\delta)}{2\cos\delta}\right)^2} \quad (6)$$

Finally, the smoothing height of the waviness profile during gear milling for a normal distribution law is determined from the equation:

$$W_p \approx 0{,}5 W_z\,. \quad (7)$$

RESULTS AND DISCUSSION

Experimental verification of the obtained theoretical equations was performed during gear milling with cemented carbide milling hob cutting tool, during high-speed gear milling of cylindrical gears with modulus m = 16 mm from 40X steel. Calculation and experimental verification data are shown in Figures 2 and 3.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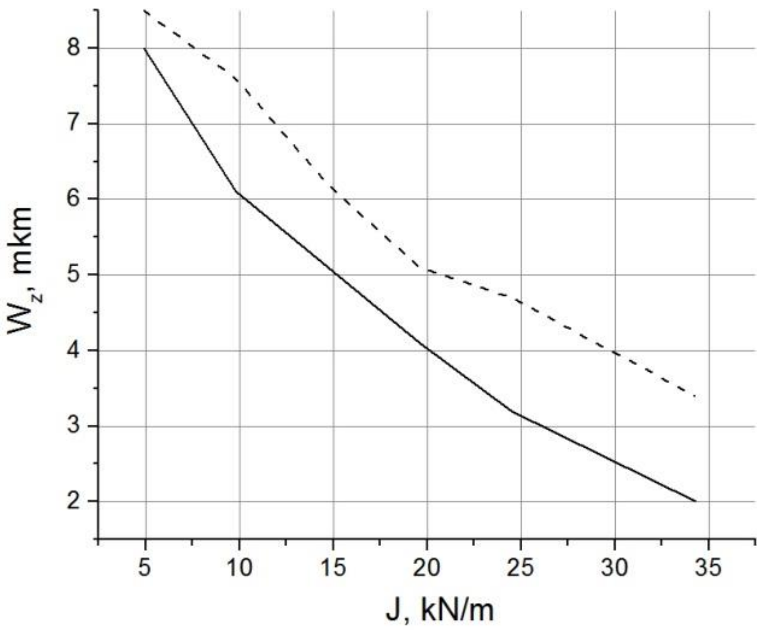
W_z, mkm
J, kN/m

a)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W_z, mkm
J, kN/m

b)

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Figure 2 - Dependence of the wave height *Wz* on the stiffness of the dynamic technological machine system (*j*) during:

a) – gear milling (v = 2.5 m/s, t = 2.25 mm, S_{min} = 50.0 mm/min)
b) – high-speed gear milling (v = 5.8 m/s, t = 2.25 mm, S_{min} = 50.0 mm/min)
solid lines - theory, dashed - experiment

The analysis of the research results shows that the main influence on the waviness during high-speed gear milling is exerted by the stiffness of the technological system, speed, feed, and the coefficient of formation of the surface layer. As can be seen to reduce waviness during processing, it is necessary to increase stiffness of the technological system. Calculation results supported by experimental data show that while stiffness j increases by factor 2, from 10 to 20 kN/mm, total waviness declines by 40% during gear milling (v = 2.5 m/s). And there will a drop of 30% in *Wz* value in case when the same stiffness growth is observed while high-speed gear milling is performed at cutting speed v = 5.8 m/s.

CONCLUSION

As in the case of roughness, the phenomenon of technological heredity is especially pronounced in case of gear milling with cemented carbide milling cutting tool, during high-speed gear milling: the height of the resulting waviness depends on its initial value; the value of the initial roughness and physical and mechanical properties of the processed gear. As well as this to reduce waviness during processing, it is necessary to increase stiffness of the technological system. All these aspects were taken into account and the expression was proposed which allows one to calculate total value of waviness W_z formed on the involute surface of a cylindrical gear. Calculations showed a close trend compared to the relevant experimental data: an increase of the MTDTS stiffness leads to the linear decrease of the total waviness height. While j doubles its values from 10 to 20 kN/mm, W_z will be decreased by 30 to 40 % and lower effect is inherent for high speed gear processing.

List of symbols

Wz – total waviness height

H_1, H_2, H_3 – components of waviness

Wz init – initial waviness height

Rz init – initial roughness

c_y – the amplitude of the main oscillation

A_{hob} – cutting tool oscillation amplitude

f_n – oscillation frequency

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l_0 – circular segment length of a milling tool teeth cut

v – cutting speed

S – feed rate

t – material component of the profile Rmr(c)

d – cutting tool diameter

D – workpiece diameter

ω – natural-vibration frequency

λ – vibration damping coefficient

T – cutting depth

h – roughness profile height

ρ – cutting edge radius

v_d, v_{cr} – cutting speed of milling tool and axial feed speed

y, n, x, x_{p0} – empirical coefficients

P – thrust component of the cutting force

Wp – smoothing height of the waviness profile

j_{DTMS} – stiffness of the dynamic technological machine system

HB – hardness of the workpiece

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